IntechOpen

Problems, Perspectives and Challenges of Agricultural Water Management

Edited by Manish Kumar

PROBLEMS, PERSPECTIVES AND CHALLENGES OF AGRICULTURAL WATER MANAGEMENT

Edited by **Manish Kumar**

Problems, Perspectives and Challenges of Agricultural Water Management
http://dx.doi.org/10.5772/2488
Edited by Manish Kumar

Contributors

Nasima Chowdhury, Tim Aus Der Beek, Milan Cisty, Wim Van Averbeke, Mohammad Albaji, Kazunori Takahashi, Seiichiro Kuroda, Jan Igel, Holger Preetz, Lucieta Guerreiro Martorano, Homero Bergamaschi, Rogério Faria, Genei Dalmago, Luca Giraldo, Gabriele Dono, Fernando Visconti, José Miguel De Paz, Francine Rochford, Meijian Bai, Di Xu, Yinong Li, Shaohui Zhang, Kristoph-Dietrich Kinzli, Lidija Tadić, Salwa Saidi, Salem Bouri, Hamed Ben Dhia, Brice Anselme, Alejandro Zermeno-Gonzalez, Abdou Sene, Mouhamadou Samsidy Goudiaby, Gunilla Kreiss, Abbyssinia Mushunje, Hang Zheng, John Derek Lea-Cox, Maria-Angeles Fernandez-Zamudio, Francisco Alcon, Maria-Dolores De-Miguel, Anindita Sarkar, Narendra G. Shah, Ipsita Das

First published in Croatia, 2012 by INTECH d.o.o.
eBook (PDF) Published by IN TECH d.o.o.
Place and year of publication of eBook (PDF): Rijeka, 2019.
IntechOpen is the global imprint of IN TECH d.o.o.
Printed in Croatia

Legal deposit, Croatia: National and University Library in Zagreb

Additional hard and PDF copies can be obtained from orders@intechopen.com

Problems, Perspectives and Challenges of Agricultural Water Management
Edited by Manish Kumar

p. cm.

ISBN 978-953-51-0117-8

eBook (PDF) ISBN 978-953-51-5233-0

Meet the editor

Dr Manish Kumar is a faculty member at Tezpur Central University, Assam, India. He earned his PhD in Environmental Engineering from the University of Tokyo, Japan, and has received many prestigious fellowships, such as Japan Society for the Promotion of Science (JSPS) foreign researcher fellowship, Brain Korea (BK)-21 post-doctoral fellowship, Monbukagakusho scholarship, Linnaeus-Palme stipend from SIDA, Sweden, Research Fellowship from CSIR, India, etc. Dr Kumar is active in the fields of hydrogeochemistry, diffuse pollution, urban and agricultural water management, and has more than three dozen publications in reputed journals, books and refereed conferences. He has been working as a referee for many reputed journals, such as *Chemosphere, Journal of Hydrology, Environmental Research Letter, Contaminant Hydrology* etc. Currently, he is a member of the editorial board for two international journals, and his name appeared in the 2010 Edition of Marquis' Who's Who in the World. Dr Kumar has also co-edited a book titled *Groundwater Monitoring and Management through Hydrogeochemical Modeling Approach*.

Contents

Preface

Food security emerged as an issue in the first decade of 21st century, questioning the sustainability of the human race, which is inevitably related directly to agricultural water management. In the context of irrigation water use, common resource management at community scale, stake holder participation and related economical issues play a vital role, but scientific precise monitoring and assessment have also become important for developing new strategies and technology to sustain increasing food demand, which is why academics and scientists from various disciplines have been involved in the development of an appropriate basis for understanding and management of the irrigation related issues. The purpose of this book is to bring together and integrate in a single text the subject matter that deals with the equity, profitability and irrigation water pricing; modeling, monitoring and assessment techniques; sustainable irrigation development and management, and strategies for irrigation water supply and conservation. The book is divided into four major sections dealing with the subjects mentioned above, and is intended for students, professionals and researchers working on various aspects of agricultural water management. Each section is comprised of at least six chapters from various research groups and individuals working separately. The book seeks its impact from its diverse topic coverage, revealing situations from different continents (Australia, USA, Asia, Europe and Africa). Various case studies have been discussed in the chapters to present a general scenario of the problem, perspective and challenges of irrigation water use.

The first section highlights the concern of equity in access to irrigation water across different classes of farmers and focuses on the consequences of unequal access to irrigation water by analysing the inequity in net returns to agriculture among agricultural communities. This section critically evaluates the benefits and uses of irrigation development to the smallholder farmers and prioritizing the need of water rights. It also emphasizes the current European Water Framework Directive (WFD) that proposes establishing a pricing policy, as well as how public institutions and water markets have evolved over time in response to changes in irrigation technology, and how they affect the cost and price of irrigation water.

Section two focuses on analyzing the impact of water withdrawals on the existing water resources of semi-arid regions in Mediterranean countries in order to evaluate the consequences for sustainable water management. It also deals with a new approach, Ground-penetrating radar, as a tool for monitoring the irrigation process, and describes in detail the instrumentation of the farm fields, including soil moisture sensors and low-cost flow measuring devices. This section is particularly useful to the readers dealing with instrumentation, because a complete description of the characteristics of different methods, such as gravimetric, neutron probe, time domain reflectometry (TDR), tensiometer, resistance block and soil psychrometer for determining soil water content is discussed, followed by a summary of the pros and cons of certain Wireless Sensor Networks for Precision Irrigation Scheduling. The section is concluded with a comparison of the different types of irrigation techniques in the southwest of Iran.

Section three is intended for researchers that are trying to find ways to apply new age technologies for sustainable irrigation development and management. This section begins by introducing a unique approach to the overall concept of groundwater resource management and emphasizes GIS techniques as a tool for groundwater vulnerability assessment in arid to semi arid climate regions. It proposes the idea of developing optimum guidelines for soil, water and crop management in irrigated salt-threatened areas under various climates, which has been a major challenge in achieving the green revolution, based on the experiences obtained in the case of sub-Saharan Africa. This section is extremely valuable for understanding the irrigation industry reforms in northern Victoria, Australia. It provides a single platform for the readers to get an overview of the social, political and legal context of the reforms, with consideration of the national cooperative agreement.

The final section of the book deals with the formulation of cutting edge strategies for sustainable irrigation water supply and conservation through innovative techniques. The section begins with an example of “Hydrogel Polymers and Antitranspirant” use to conserve irrigation water in arid and semi-arid regions. An algebraic approach for evaluating the influence of spatial variability of field microtopography on irrigation performance by numerical simulation is also proposed, along with a new hybrid approach using a combination of the differential evolution and linear programming methodology for determining the minimal cost of the design or rehabilitation of a water distribution system. This section is useful to the policy makers that are working on issues of revitalisation and management of smallholder irrigation schemes as a part of rural and per-urban economic development strategy, aimed at creating or improving livelihoods.

It is evident but nevertheless worth mentioning that all the chapters have been prepared by individuals who are experts in their field. The views expressed in the book are those of the authors and they are responsible for their statements. An honest effort has been made to check the scientific validity and justification of each chapter through several iterations. We, the editor, publisher, and hard-working agricultural water professionals have put together a comprehensive reference book on problems, perspectives and challenges of irrigation water use with a belief that this book will be of immense use to present and future colleagues who teach, study, research and/or practice in this particular field.

Acknowledgement

I am grateful to Prof. Mihir Kanti Chaudhary, Vice-chancellor, Tezpur University, and all my colleagues at the department of Environmental Science for providing me with a comfortable ambience that helped me extend my work hours in order to complete my editorial responsibilities. On that note, I also want to extend a special thanks to both the former and the current Head of the Department (Prof. K.P. Sarma and Dr R.R. Hoque respectively). I also owe a special mentioning to people whose support was vital, like Dr Nawa Raj Khatiwada of NDRI (Nepal), Dr S. Chidambram of Annamalai University, Dr B. Kumar, Dr M.S.Rao and Dr G. Krishnan, (NIH, Roorkee), Ms. Awalina Satya (Indonesia) and last but not least Dr S. S. Bhattacharya, TU. Although I cannot list all the names, it is impossible to skip acknowledging all the authors that contributed their scientific work, Mr. Dejan Grgur for his hard and persistent efforts in rigorous communications as a Publishing Process Manager, Ms. Aparna Das and Mr. J.P. Deka for helping me in efficient work management, Ms. Rashmi Singh (My wife) for taking care of me and my sons Aayush and Akshit, blessings of my parents and good wishes of all the well wishers which made it all possible.

Dr. Manish Kumar
Assistant Professor, Department of Environmental Sciences
Tezpur University Napaam
Sonitpur Assam
India

Part 1

Equity, Profitability and Irrigation Water Pricing

1

Equity in Access to Irrigation Water: A Comparative Analysis of Tube-Well Irrigation System and Conjunctive Irrigation System

Anindita Sarkar
Department of Geography, Miranda House, Delhi University, City, Delhi India

1. Introduction

Access to irrigation water is one of the most important factors in modern agricultural production. It offers opportunities for improving livelihoods particularly in rural areas as access to reliable good quality irrigation reduces the cost and increases the quantum of production by reducing the risks faced by the rain fed agriculture. In agricultural water distribution, equity is limited to allocation and receipt of irrigation water. Equity means fairness in creating fair access to water for all, both within and between communities and within and between regions. Since more than 60% of the irrigated area is under groundwater and is fast increasing with time, the equity in access to groundwater is of great concern. It is noteworthy to mention that in the Indian context water allocation principles refer to 'proportionate equality' and 'prior appropriation'. The former operates in the existing inequality of land ownership and the later generates inequality through uses (Pant 1984).

By the very nature of the resource, groundwater development is largely by private initiative of farmers which is conditioned by their size of land holding, savings and investment capacities. Because of this reason in the first phase of groundwater exploitation, the poor invariably got left out in the race for groundwater irrigation and decades later when they began to enter groundwater economy a set of new rules and regulations like licensing, sitting rules and groundwater zones made their entry difficult in most areas and impossible in those areas where groundwater overdraft was high (Shah 1993). With intensive groundwater exploitation, declining water tables have further reduced access to groundwater irrigation to a large number of small and marginal farmers who can neither use traditional techniques nor are able to use 'lumpy' new technology so as to pump water at an economic price. Moreover, chasing water table is beyond the reach of resource poor farmers. In such conditions they have to depend on the other well owners for groundwater irrigation. This has severe equity implications especially in a situation where farmers have little opportunity to earn their income from sources other than irrigated agriculture (Dhawan 1982). Thus in the process, the race to exploit groundwater resource is exponentially continued by the haves and the have-nots continue to bear the brunt of this negative externality (Nagraj and Chandrakanth 1997). As a consequence, there emerges widespread apprehension that, instead of reducing relative inequalities among rural incomes, groundwater irrigation development may actually have enlarged both the absolute and relative inequalities already prevalent (Shah 1987 and Shah 1993). Many micro level studies have also highlighted these serious equity implications of groundwater exploitation with falling water levels particularly in the water-starved regions (Shah 1991, Bhatia 1992, Monech 1992, Nagraj and Chandrakanth 1997). While groundwater availability can be studied from an earth science perspective but to analyse its accessibility one needs deeper understanding of groundwater economy and its underlying socio economic dynamics.

The policy design aimed to achieve food security of the country in the sixties encouraged "grain revolution" with increasing area under water intensive rice-wheat cropping pattern in the Green Revolution belt making Punjab the 'Bread basket' of the country. During this time, the modern agricultural practices of HYV technology in Punjab also ushered in the shift from canal irrigation to tube-well irrigation as it was a more reliable and flexible source of irrigation and this gave boost to enormous increase in agricultural production. In the early phase of Green Revolution, rapid diffusion of groundwater technology was thus appreciated on grounds of it being economically superior to other sources of irrigation in terms of its efficacy and productivity (Dhawan 1975). The superiority of this irrigation source continued to enhance the intensive cultivation of water intensive crops on an extensive scale not withstanding the hydro-geological thresholds of this resource. Consequently the over exploitation of groundwater inevitably questions the accessibility of this resource and rises serious concerns about the equity in its distribution.

Literature highlighting the superiority of the modern water extraction machines has been too preoccupied with highlighting the superiority from individual or private point of view which only focuses on economic justification and economic efficiency without considering the economic equity. It should be noted that economic efficiency begins to introduce a concern for equity that was missing in economic justification, in the specification that the increase in welfare of one individual should not be at the expense of another. The economic justification although assures enough benefits generated to cover all the costs but do not take into account the economic equity criterion which requires the costs to be allocated in proportion to benefits received (Abu-Zeid 2001).

In this broader context, the paper examines three aspects inequity in access to groundwater irrigation across different classes of farmers in different phases of groundwater depletion in Punjab. The study analyses the external diseconomies in groundwater utilization in terms of its accessibility to groundwater irrigation to large farmers vis-à-vis the small and marginal farmers. Firstly, it looks into the determinants of groundwater accessibility. Secondly, it empirically shows the difference in the physical and economic accessibility of groundwater resource and thirdly it evaluates the consequences of unequal access to groundwater irrigation by analysing the inequity in net returns to agriculture among agricultural communities dependent on groundwater irrigation.

Since depletion is a phenomenon, to capture the effects of groundwater depletion, in this study three villages are chosen from the same agro-climatic region with different levels of groundwater depletion. Three hundred households are interviewed from each village to collect field level data for the analysis. Table 1 gives the profile of the three study villages and figure 1 shows their locations.

Name of the Village	Tohl Kalan	Gharinda	Ballab-e-Darya
Slope	Gentle	Gentle	Gentle
Prevalent Soil Type	Alluvial	Alluvial	Alluvial
Average depth of water table below	12 meters	18 meters	46 meters
Type of irrigation	Mixed	Groundwater	Groundwater
Sources of Irrigation	canals – 43 % tube-wells – 57 %	tube-wells – 100 %	tube-wells – 100 %
Cropping Intensity (%)	204	217	178

Table 1. Profile of Study Areas

2. Determinants of groundwater accessibility

Studies have indicated that ownership and access to groundwater irrigation has almost replaced land in determining one's socio-economic and political status (Janakarajan S. 1993). In the groundwater dependant societies, the struggle for access to, and control over groundwater, shapes the course of agrarian change and development (Dubash 2002). Certain factors which govern the ownership of groundwater are central to understanding changes in access to groundwater over time. Under British common law, the basic civil law doctrine governing property ownership in most of India, groundwater rights are appurtenant to land (Singh 1992). If a person owns a piece of land, he/she can drill or dig a well and can pump out as much groundwater as he/ she is able for use on overlying lands. When land is sold the groundwater access rights pass with the land and can not legally separated from it. At present, groundwater rights are defined by the ability to chase water tables and ability to invest in changing water technology. If one can afford to deepen ones well, the water pumped out from it is theirs (Moench 1992). Groundwater accessibility is thus largely depend on a wide interplay of interconnected factors like land holding size, type and nature of ownership of tube-wells, productivity of tube-wells and density of tube-wells. The following section analyses the interplay of these dynamic factors among various size classes of farmers at different levels of groundwater depletion to understand the variability of groundwater accessibility with continuous resource depletion.

2.1 Land ownership and accessibility to groundwater

The distribution of land ownership and the extent of land subdivision and fragmentation affect the development and use of groundwater. Jairath (1985) argues that fragmentation of landholdings has led to underutilization of privately owned tube-wells in Punjab. Thus large farms may more beneficially utilize groundwater irrigation structures than the small ones. Moreover the higher farm productivity of large farms also facilitate the greater investments in buying and maintaining tube-well technology which is essential for continued accessibility of groundwater irrigation (Dubash 2002). Inequalities in the ownership of water extraction machines are closely related to the inequalities in land ownership and the inequalities in land and water ownership are seen to compound each other (Bhatia 1992). Thus the pattern of land ownership inevitably influences the farmers' ability to access groundwater and since availability of groundwater varies according to the levels of the existing water table, it is important to examine how different land holding categories at different levels of resource depletion differ in access to groundwater irrigation.

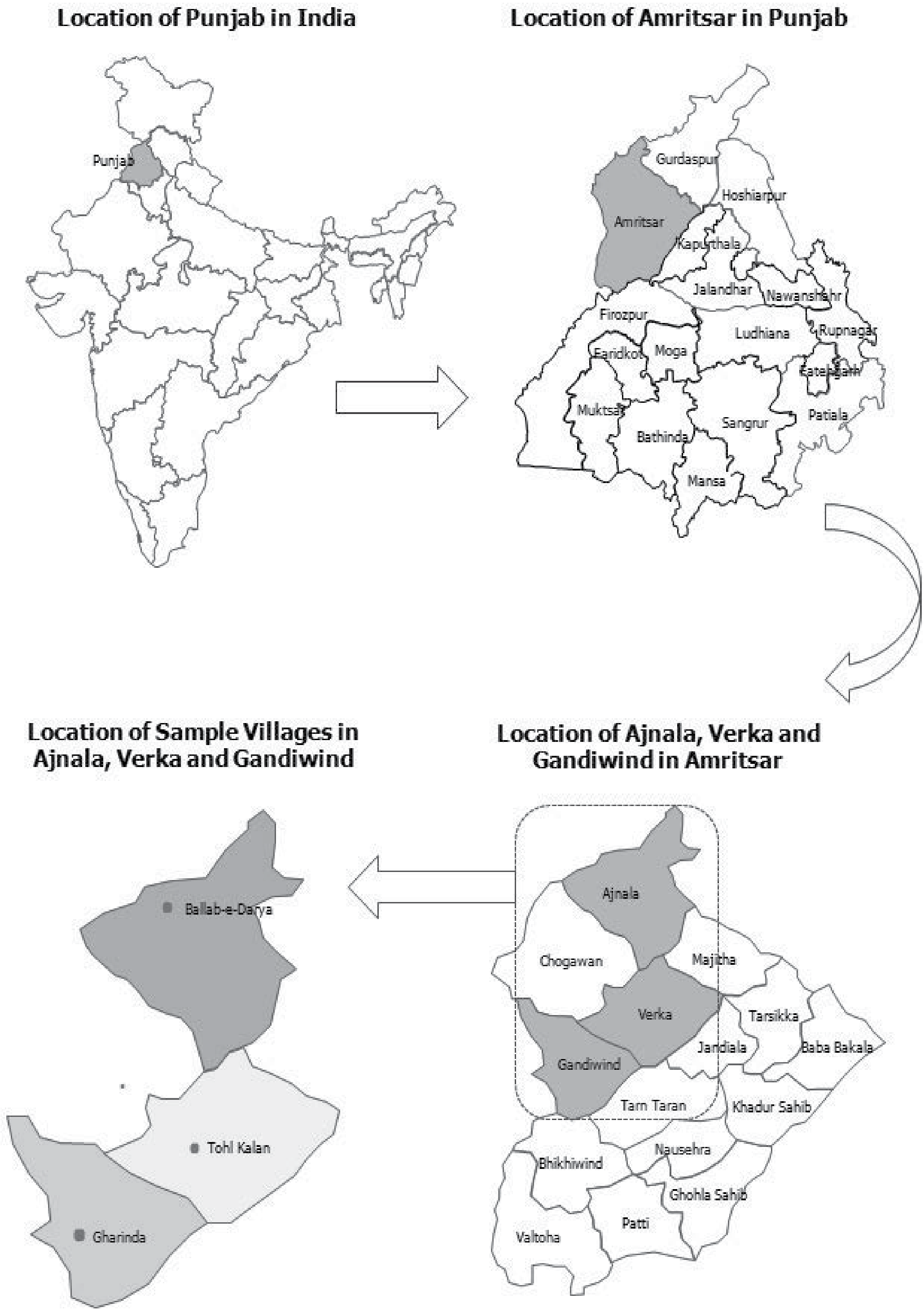


Fig. 1. Location of Study Areas

If we accept land as a reasonably good indicator of power in agrarian societies, then all the sample villages are societies with deep inequalities of power (Table – 2). Landownership and land operation through tenancy are linked in a way that they defy easy separation. Studies show that in Punjab "reverse tenancy" is a common phenomenon under which small and marginal farmers lease out land on cash terms to the medium and large farmers who have sufficient capital and have made investment in machinery and in water extraction machines (Siddhu 2002). A careful examination (Table–3) reveals that reverse tenancy is

Land owned (acres)	Mixed Irrigation Village (Tohl Kalan)	Tube-well Irrigation Village (Gharinda)	Tube-well Irrigation Village with Problems of Depletion (Ballab-e-Darya)
1 - 2	18	4	32
2 - 4	26	6	15
4 - 10	38	32	32
more than 10	18	58	21
Total	100	100	100

Source: Questionnaire surveys in various villages from May to July, 2009

Table 2. Land Ownership by Different Classes of Farmers (Percentages)

Land owned (acres)	% of households in each group	% of households leasing in	% of households leasing out	leased in area as % of operated area	leased out area as % of operated area
Mixed Irrigation Village (Tohl Kalan)					
1 - 2	18	11	6	9	21
2 - 4	26	23	0	11	0
4 - 10	38	13	0	6	0
more than 10	18	50	0	28	0
Total	100	22	1	18	2
Tube-well Irrigation Village (Gharinda)					
1 - 2	4	0	0	0	0
2 - 4	6	0	0	0	0
4 - 10	32	9	0	5	0
more than 10	58	17	2	5	9
Total	100	13	1	5	7
Tube-well Irrigation Village with Problems of Depletion (Ballab-e-Darya)					
1 - 2	32	0	28	0	29
2 - 4	15	0	7	0	9
4 - 10	32	13	0	5	0
more than 10	20	20	0	16	0
Total	100	8	10	10	2

Source: Questionnaire surveys in various villages from May to July, 2009

Table 3. Incidence of Tenancy by Landownership (percentage of land leased out to total land owned by each group)

prevalent in the sample villages and it is also more pronounced in the tube-well irrigated village of Ballab-e-Darya indicating close correspondence of this phenomenon with groundwater depletion.

Field observations reveal, in the tube well irrigated regions of Punjab, the small farmers who do not have their own source of irrigation and are also not in a position to buy water for irrigation are compelled to lease out their land to the large farmers especially in the kharif season when there is acute water scarcity on account of rice cultivation[1]. In spite of much exploitation, farmers prefer leasing out land in kharif season because it is still more profitable than rain-fed maize cultivation. The value of the land is calculated purely on the basis of availability of water supply for irrigation which in turn depends on the number of wells in that particular land, its depth and the capacity of the pump used to pump out water. It was seen that land endowed with sufficient groundwater irrigation was leased out at Rs 16,000 to Rs 20,000 per acre and land without any source of water was leased out for Rs 6,000 to Rs.8, 000.

Very exploitative tenancy relations were also common in lands without any water extraction machines. In such cases the owner (mostly small or marginal farmers) pays for all the inputs like seeds, fertilizers, insecticides, labour and the produce is divided equally between the owner and the tenant. The tenant who is a large land lord only provides with the irrigation water and takes away half of the produce. Thus, ownership of groundwater determines the terms and conditions of tenancy in groundwater depleted regions in Punjab. These indicate that with groundwater depletion, water becomes the most important factor of cultivation and even its importance exceeds that of land. In such groundwater dependant societies, land has no value unless it is endowed with water extraction machines and the bargaining power is also in the hands of those who own water along with land and not only land. Thus, there is a complete shift of power relation from the hands of 'landlords' to 'waterlords'.

The control and access over groundwater offers scope for interlinkages between ownership of land and water. Such 'interlinked contracts' have been observed for land, labour and credit, and similar contractual forms in the provision of irrigation may be an additional mechanism of marginalising resource poor to groundwater access. The link between credit and groundwater has several possible implications. Usurious credit relations driven by groundwater related investment, carry the potential for a long term debt trap. They also allow a creditor to dictate production decisions especially the decisions of cropping pattern. Creditors are mostly landowners, leading to credit relations being 'interlinked' with land and water arrangements in various combinations. In the villages of Punjab, such interlinked 'land-water-credit markets' were very common especially in regions of acute depletion. Interlinkages between these three important determinants of cultivation have lead to sever consequences in accessibility to groundwater irrigation and hence a profitable agriculture. Institutional credit is not available to set up new tube-wells and land without water can not be cultivated. Farmers owning smaller assets (lands) thus often fall prey to local money lenders. As cost of inputs increase with time, credits become a necessary condition to sustain cultivation. The farmers owning small land holdings without any water extraction machine have no alternative option but to take loan from local money lenders or lease out or sell out

[1] Rice and maize are grown in Kharif season. But the relative profitability of growing rice is much higher than maize. This is a half yearly lease.

his land. Thus, the interlinking of credit, land and water leads to much greater exploitation of the less endowed farmers and in the process they lose their land and turn into agricultural labourers or construction workers in urban areas from a cultivator.

2.2 Ownership of wells and access to groundwater

In agrarian societies heavily reliant on irrigated agriculture, control over water is an essential complement to landownership (Dubash 2002). Available evidences in literature indicate strong positive correlation between land holding size and ownership of modern water extraction machines (Shah 1988) which is also true in all the three sample villages (Table - 4). Since the development of a well for irrigation requires substantial investments, it is largely affordable by the resource rich farmers who are also the large landlords. This implies that better access to land is associated with the better access to groundwater. Along with this, the inequality in the distribution of operational tube-wells is most pronounced in the groundwater depleted village because with receding water tables more numbers of wells of small and marginal farmers dry up as they have no capital to chase water table. Positive correspondence with landholding size and average depth of tube wells and average land irrigated per bore well reiterating the same findings (Table - 4). Thus, along with the inherent inequality of tube-well ownership influenced by the unequal distribution of land ownership, groundwater depletion further increases the skewedness in the ownership of tube-wells.

Particulars	*Marginal Farmer*	*Small Farmer*	*Medium Farmer*	*Large Farmer*	*Total*
Mixed Irrigation Village (Tohl Kalan)					
Average no of operational tube-wells (feet)	0.72	0.96	1.00	1.00	0.94
Average Depth of tube well	180	191	231	421	249
Average land irrigated per bore well (acre)	4.42	7.05	12.99	40.56	15.50
Tube-well Irrigation Village (Gharinda)					
Average no of operational tube-wells (feet)	1.00	1.00	1.06	1.34	1.22
Average Depth of tube well	120	185	210	217	209
Average land irrigated per bore well (acre)	2	4	7	13	10
Tube-well Irrigation Village with Problems of Depletion (Ballab-e-Darya)					
Average no of operational tube-wells (feet)	0.41	1.00	0.91	1.80	0.94
Average Depth of tube well	120	185	210	217	209
Average land irrigated per bore well (acre)	2	4	7	13	10

Source: Questionnaire surveys in various villages from May to July, 2009

Table 4. Tube Well Ownership and Area of Influence of Tube Wells across Farm Size Classes (Change into percentage)

Moreover, the poor farmers even after owning wells may be trapped in a regime of low well yields as not only water table is receding progressively but also many new wells are dug[2]. Because of declining water tables and increasing density of wells, it is difficult to access a new location to fix up a new well which is a necessary condition to avoid well interference and hence have a productive well. Large farmers owning large plots of land have greater opportunity to space his wells. On the contrary, the small and marginal farmers have little option to get a suitable place to dig his well as he owns a small fragment of land and very often he is a late initiator of the tube-well technology and the neighbouring plots already have deep tube-wells.

2.3 Nature of ownership of wells and access to groundwater

In Punjab, some of the most important factors affecting access to groundwater irrigation include whether wells are owned solely by individuals or held jointly. It is seen that the average individual ownership of tube-wells is much higher for large landowners than the marginal and small land owners (Table -5). The strong preference of individual ownership of tube-wells despite the higher costs involved reflects that individual exploitation of water even at higher costs is sufficiently productive to be economical. Individuals may also be prepared to bear higher costs because of difficulties in ensuring effective joint ownership and management of wells, and the risks depending on purchases from other tube-well owners. In conditions of continuous groundwater mining even available supplies are inadequate to meet the demand of the area served by an aquifer, these constraints become more severe (Janakarajan and Moench 2006). This fact is also reinforced by the much higher average number of sole ownership of tube-wells in the groundwater depleted village of Ballab-e-Darya than in the other two villages (Table-).

The incidences of hiring of tube-wells were not common phenomena in the villages because land and water extraction machines was considered as complementary resource and the leasing in and leasing out of land automatically resulted in the leasing in and leasing out of the tube-well in the respective land. Hiring of tube-wells also does not show any correspondence with land holding size. With groundwater depletion the farmers do not want to hire wells as disputes arise as to which party will deepen the well and repair the pump which becomes a hurdle for timely irrigation. The farmers, thus, prefer to lease out the entire land and tube-well to have complete control and responsibility of the tube-well. Due to these impediments of groundwater accessibility through hired tube-wells, hiring has become redundant in the villages of Punjab.

Since tube wells are indivisive, with successive generation number of land holdings increase and the numbers of shareholders consequently increase in a family owned well. Sometimes even the partners (subsequently the heirs of the partners) of the old water extraction technology like *hult*[3] continue to jointly irrigate and own wells. In many cases especially for newly owned joint wells, either the brothers and cousins or neighbouring farmers owning small fragments of (contiguous) land contribute jointly to install submersible pumps. Joint wells are commonly operated by installing a single pump set

[2] With many wells, the density of tube-wells increases lowering the yield of the neighbouring wells.
[3] *Hult* was a traditional water extraction machine and it needed lot of labour (both animal and human) to irrigate land. As it was labour intensive families jointly owned and operated *hults*.

and running the motor in rotation between shareholders for a fixed number of hours. It helps them to share the cost and also fully utilize the chunk of economic investment for (jointly) irrigating the combined portion of land. With the incresing number of joint ownership of wells, the dilemma and uncertainties associated with management of jointly owned wells create varied nature conflicts within communities and families which is important to analyse as it revolves round several issues of equity to accessibility of irrigation water among the shareholders.

Land Holding Category	*Solely Owned Tube-Wells*		*Hired Tube-Wells*		*Jointly owned Tube-Wells*		*operational Tube-Wells*	
Mixed Irrigation Village (Tohl Kalan)	*No*	*%age*	*No*	*%age*	*No*	*%age*	*No*	*%age*
Marginal Farmer	7	9	5	28	12	29	16	16
Small Farmer	22	28	6	33	11	26	26	27
Medium Farmer	32	41	3	17	14	33	38	39
Large Farmer	17	22	4	22	5	12	18	18
Total no of wells	78	100	18	100	42	100	98	100
Tube-well Irrigation Village (Gharinda)								
Marginal Farmer	4	3	0	0	0	0	4	3
Small Farmer	6	5	0	0	0	0	6	5
Medium Farmer	31	26	0	0	3	100	34	28
Large Farmer	77	65	1	100	0	0	78	64
Total no of wells	118	100	1	100	3	100	122	100
Tube-well Irrigation Village with Problems of Depletion (Ballab-e-Darya)								
Marginal Farmer	7	9	0	0	4	27	13	14
Small Farmer	5	7	0	0	10	67	15	16
Medium Farmer	28	37	0	0	1	7	29	31
Large Farmer	36	47	0	0	0	0	36	39
Total no of wells	76	100	0	0	15	100	93	100

Source: Questionnaire surveys in various villages from May to July, 2009

Table 5. Types of Tube Well Ownerships across Farm Size Classes

Data reveals that joint ownership of wells mostly rests with small and marginal farmers (Table-5). Large farmers mostly have wells under individual ownership. In some cases they consolidate their shares in the wells by purchasing from other shareholders. A positive correspondence is also noted for incidence of joint ownership and groundwater depletion (Table - 5). With depletion, the running cost of groundwater irrigation increases as continuous deepening becomes mandatory to sustain tube-well irrigation. In such situations the joint ownership helps the small and marginal farmers to share the cost and have access to groundwater irrigation. The cost of the well is borne by all the share holders in proportion to the number of shares they own and the proportion of the land they will be irrigating with the help of the shared water extraction machine. In cases where the shareholders don't cover their proportion of the costs, they are excluded from use of the pump set. If a shareholder voluntarily withdraws his share from a joint well the remaining shareholders contribute money to take out his share. The maintenance and deepening of the well is also jointly done by all the share holders.

In reality, however, the cost benefit sharing of the jointly owned wells are much more complex. While the details of the management of jointly owned wells for every case is not documented in detail, but interviews suggest that the incidence of conflict in the process of sharing of water from jointly owned wells is widespread and that practical difficulties surrounding pumping and management of shares and ownerships are of the most important source of conflict which often results in differential access between dominant owners and others who are less capable of exercising their partial ownership rights. Where scarcity is an issue, rights are likely to come in conflict. Conflicts among the shareholders are common regarding the number, spacing and time of the 'turns'[4] in irrigating their respective farms. The disputes are countless during the kharif season when virtual scarcity of water increases with cultivation of rice. Many disputes also arise due to the erratic power supply[5], which disrupts schedules for sharing available pumping time. Village panchayats (informal village courts) are often involved in resolving such disputes but conflicts continue to resurface in the next period of scarcity. Many disputes are only resolved when one shareholder buys the others out. In some cases this is accomplished by poor farmers selling their land along with their shares in a well. In addition disputes often occur over the need to deepen wells. Shareholders with different land holdings disagree regarding the distribution of the benefits from well deepening and one or more refuses to contribute to the cost. There are also instances of cases where wells are abandoned due to prevalence of too many shareholders and the emergence of numerous disputes. Conflicts were even noticed in cases where farmers voluntarily wanted to take out his share for reasons like migrating to urban areas or abroad, changing occupation, buying land somewhere else or even setting up individual well. The shareholders do not agree to pay for the withdrawn share in the joint wells. In such cases, the individual (who wants to leave the partnership) either goes without getting his share paid or sell off his land. Conflicts in crop selection were also common where some shareholders wanted to grow some other crop but could not do so because of the collective decision of the shareholders. In well sharing per person availability of water also declines (especially with incessant falling of water tables), the shareholders have to wait for their turns to irrigate their crop. This reduces the quality of irrigation as both availability and the control over the water supply decline.

While sharing of water from a joint well is often problematic, positive features also exist. The fact that about 62 % of the jointly owned wells are accessed by farmers owning less that 4 acres of land indicates greater groundwater accessibility to the small and marginal farmers through this system. In the villages there are informal rules governing the sharing of costs and benefits from a jointly owned well and village *panchayats* play a role in redressing disputes. Thus, joint ownership system promotes accessibility to groundwater irrigation and particularly benefits those who can not afford a well of their own because of lack of resource

[4] A specific number of hours and a specific time are fixed for each shareholder to use the pump or the tube-well to irrigate his land.

[5] During the peak time of irrigation of rice (May – June) the electricity supply in the villages on an average varies from 6 to 8 hours.

and also due to ownership of small fragments of land. While many joint wells fail due to two interrelated reasons; declining groundwater levels and the lack of finances for well deepening etc., many joint well ownership also become successful in providing groundwater access to small and marginal farmers who join hands in the time of scarcity to jointly harness and share the benefits of this (groundwater) resource which would not have been possible with individual efforts (investments). Many farmers believe that joint ownership of wells for this very reason is a better solution for groundwater accessibility especially in times of depletion but feel that joint ownership among kins and friends do not materialize as their individual small land holdings are spaced at greater distances and since joint ownership requires adjustability and compatibility to avoid conflicts the farmers are not comfortable to become partners of just any (neighbouring plot's) farmer. When the farmers of distant fields become partners in joint wells, disputes commonly arise as many farmers object to passing of irrigation pipes through their plots and mischievous incidences of damaging pipes and disrupting (stealing) water supplies takes place. In such cases when joint ownership of wells fails, they resort to buying water which not only becomes costly but also exploitative at times. While the share system (partially) promotes equity in access to groundwater, depletion reinforces inequality in the village societies where many joint owners become heavily indebted and are eventually forced to sell their shares along with their parcels of land.

3. Equity to groundwater irrigation accessibility

To examine the access to the groundwater resource, two parameters, namely, physical and economic access to the resource is discussed. The physical access to resource is the groundwater used by the farmers measured in volume (acre-hours); economic access is the cost per unit volume of water used/accessed. The equity to resource was examined by classifying the farmers in two ways – on the basis of holding size and on the basis of the different agro-ecosystems at different levels of resource depletion. It is evident that physical access to groundwater resource is skewed towards the higher landholding classes (Table- 6). The inequality to physical access to groundwater resource is due to the inequality to land holding sizes. If we negate the land holding factor and work out the physical access realised to groundwater resource on the basis of per unit of holding size for each class, we observe that the groundwater realised per acre of holding size is lowest in the groundwater depleted village of Ballab-e-Darya which indicates towards low yield of tube-wells due to progressive water table depletion. There is also inequality in water accessibility among marginal and large land holdings as farmers of marginal and smaller land holdings are incapable for chasing water tables as fast as the resource rich farmers. The per acre accessibility of groundwater is almost same among the tube-well irrigation village of Gharinda where since the water table is comparatively at shallower depths, the farmers across all categories can access groundwater. In the mixed irrigation village of Tohl Kalan the per acre accessibility to groundwater is low for the marginal farmers because most of them (marginal farmers) irrigate with canal water as investment in tube-well for small plots of lands are not economical and with availability of canal water it is also not a mandatory option. The other parameter of equity, the economic access to groundwater, is also more skewed towards the larger land holding groups (Table - 6). Thus on one hand there is worsening physical shortage of water for small and marginal farmers and on the other there is also a scarcity of economically accessible water.

Particulars	*Marginal Farmer*	*Small Farmer*	*Medium Farmer*	*Large Farmer*
Mixed Irrigation Village (Tohl Kalan)				
Total water used across all farms (acre-hour)	13208 (3)	46074 (11)	141384 (34)	219460 (52)
Water accessed per unit of holding size (acre-hour/acre)	403	593	601	817
Economic accessibility of groundwater = acre-hour of ground water per rupee of a motorised cost of well*	48624	121872	258149	831172
Economic accessibility of ground water per Rs. 1000	49	122	258	831
Tube-well Irrigation Village (Gharinda)				
Total water used across all farms (acre-hour)	4126 (1)	13128 (2)	147850 (18)	646938 (80)
Water accessed per unit of holding size (acre-hour/acre)	515.75	625.14	634.55	652.16
Economic accessibility of groundwater = acre-hour of ground water per rupee of a motorised cost of well*	64702	144432	306179	745554
Economic accessibility of ground water per Rs. 1000	64.70	144.43	306.18	745.55
Tube-well Irrigation Village with Problems of Depletion (Ballab-e-Darya)				
Total water used across all farms (acre-hour)	10702.5 (3)	27558 (8)	109765 (31)	210711 (59)
Water accessed per unit of holding size (acre-hour/acre)	365.90	314.05	442.16	565.67
Economic accessibility of groundwater = acre-hour of ground water per rupee of a motorised cost of well*	21858.81	121194	227474	708611
Economic accessibility of ground water per Rs. 1000	21.86	121.19	227.47	708.61

Note: Figures in parentheses are percentage to total and the cost is calculated as actual running cost incurred if diesel pumps were used
Source: Questionnaire surveys in various villages from May to July, 2009

Table 6. Equity to Groundwater Irrigation Accessibility for Farm Size Classes

4. Equity in net returns from agriculture

To examine the extent of inequity in access to groundwater irrigation, the extent of inequity of net returns per acre realized for different landholding size classes is taken as a proxy variable. Various measures of income inequality were estimated (Table-7) and is also presented in the Lorenz curve (figure-2). Inequality of agricultural return distribution is indicated by the degree to which the Lorenz curve departs from the diagonal line: the further the curve is from the diagonal line, the more unequal is the farm income distribution, and vice versa. For all these measures as well as the Lorenz curve, it can be

Inequity measures	Mixed Irrigation Village (Tohl Kalan)	Tube-well Irrigation Village (Gharinda)	Tube-well Irrigation Village with Problems of Depletion (Ballab-e-Darya)	Total of all samples
Gini concentration ratio (GCR)	0.070	0.008	0.218	0.099
Theil Entropy index	0.039	0.003	0.040	0.028
Standard deviation of logarithmic income	1.006	0.204	1.687	0.966
coefficient of variation	0.444	0.270	0.544	0.420

Source: Authors own calculation

Table 7. Measures of Income Inequality in Different Sample Villages

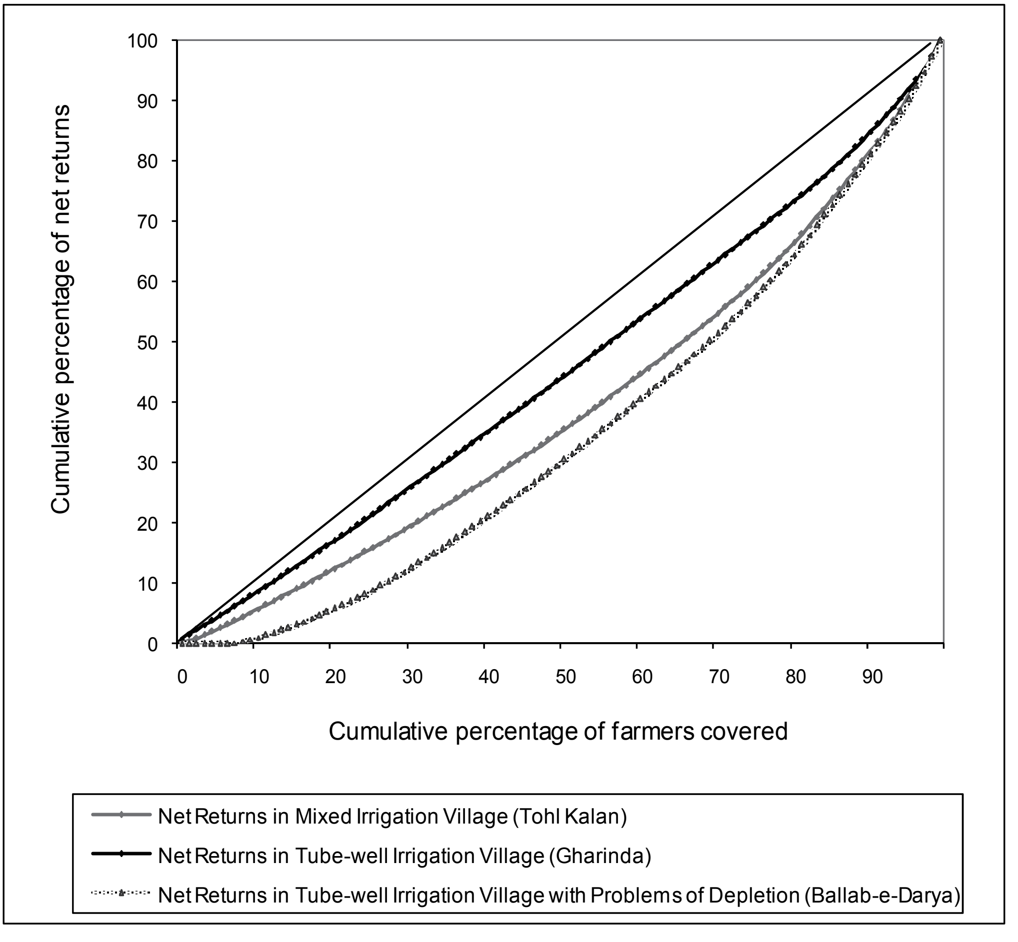


Fig. 2. Distribution of Net Returns to Cultivation

concluded that the net returns realized by farmers using groundwater irrigation in Gharinda is more evenly distributed than and in Ballab-e-Darya where there is problems of groundwater depletion. This is due to the more skewed access (distribution) to groundwater irrigation among the various classes of farmers in Ballab-e-Darya. Only a few marginal and small farmers have access to groundwater in Ballab-e-Darya on account of rising cost due to depletion. However it was not in case of Gharinda where groundwater accessibility was more equal. In Tohl Kalan the less inequality in net returns from agriculture was due to fact that a majority of small and marginal farmers who do not have tube-wells use canal water and have a large number of joint wells to supplement canal irrigation. A high proportion of marginal and small farmers being shareholders in joint wells in Tohl Kalan reduce inequality in resource among the different classes of farmers and thereby to irrigation surplus. But in Ballab-e-Darya due to deeper water tables and progressive receding of water table, the investment costs and maintenance of water yield in wells are very high. So the marginal and small farmers are fearful to go in for new bores on an individual as well as joint basis, thereby limiting their access to the resource. The non existence of any subsidiary source of irrigation other than tube-well irrigation further worsens the inequality in groundwater access and income distribution in Ballab-e-Darya. This shows that groundwater depletion plays a major role in inequitable distribution of groundwater irrigation access in a water scarce region like Punjab.

5. Conclusion and policy implication

The study reinforces the fact that growing inequity in access to groundwater leads to a process of continued social differentiation, which results in deprivation, poverty and the consolidation of inequitable power relations within local communities. Declining water levels and overexploitation of groundwater further leads to equity and sustainability problems and deteriorating socio-economic conditions. The immediate consequence of groundwater depletion is linked with the increasing cost of groundwater irrigation in terms of both capital and operating costs which is an increasing function of depth of water table. If the receding water table becomes a common phenomenon, the cost of groundwater irrigation rises in perpetuity. In case of considerable decline in water table, the external effect could not be only extra capital and operational costs but also lower farm output because of either reduced availability of water or lesser use of water at the enhanced cost of lifting it, or both. When the enhanced cost of water lifting exceeds the benefits from the use of such water for small farmers with traditional modes of groundwater irrigation that they are forced to give up irrigated farming altogether. Thus with continuous decline in the water table, the small and marginal farmers get deprived of groundwater or pay higher irrigation charges or they adjust their agriculture operations according to the accessibility of the water which largely depend on the tube-well owners who are generally large framers. This increase cost and severely affects the small farmers' production in the long run.

In the last twenty years gradual increase in groundwater access has undermined maintenance of canal irrigation systems Punjab which is evident from the government statistics which shows net area irrigated by canals has been declining and at present it is less than 27%. Field investigations reveal that the actual area under canal irrigation is further less as most of the canals have dried up and there is hardly any supply of canal water. Lack of maintenance of canal network and declining public investment in canal infrastructure have consequently led to shrinking area under canal irrigation further compelling the farmers to increasingly depend on groundwater for irrigation. It seems that the subsidy in irrigation has shifted from canal subsidy to electricity subsidy in agriculture in Punjab to the extent that agricultural electricity is free in Punjab. In the process it has shifted the determinants of water access away from communities and into the hands of few resource rich individuals who can invest capital in upgrading water technology and continuously deepen wells with depletion.

This has broader repercussions in the agricultural communities in Punjab. Firstly with an inherent inequality attached to groundwater ownership and accessibility on account of being privately initiated and monitored, the electricity subsidy consequently is disproportionately shared. But with declining water tables (for which large farmers are more responsible as they pump out more water and have large plots of land), the small and marginal farmers lose out on improvising their groundwater technology and competitive deepening and in the process get increasingly excluded form the financial grants (in this case free electricity) given by the government to facilitate the farmers to augment agricultural production. Secondly, when canal water is available in the villages, the small and marginal farmers (can at least) avail of irrigation water from canals or use canal water supplemented by tube-well water even when they do not own groundwater technology which (as of now)[6] is entirely a private initiative to start with and maintain. So in such cases where canals exists, these marginalised farmers can at least use some form of government grant (the canal water subsidy) to augment production (if not the groundwater subsidy) rather than being completely deprived. But the irony is that, the canal water subsidy although exists, due to lack of maintenance, most of the canals have dried out leaving the farmers no option but to depend on groundwater for irrigation. Thirdly, since this (electricity subsidy) financial assistance is not 'targeted' it is (mis)appropriated by the wealthy and does not reach the needy farmers who actually require this support. Lastly, the electricity subsidy is enhancing groundwater depletion which in turn is enlarging the gap between the rich and the poor making the agriculture ecologically unsustainable and socially impoverished in Punjab.

In the absence of surface water irrigation, groundwater withdrawals will tend to outstrip the groundwater recharge, with consequent downward pressure on the water table. In the presence of canal irrigation the pressure on water table eases in two ways: part of the demand for irrigation water shifts to canal water and seepage from unlined part of the canal network augments groundwater recharge. Thus a policy of simultaneous development of surface and groundwater irrigation will prevent permanent decline of water table in arid or semi-arid or low rainfall areas because of over-exploitation of groundwater which in the long run will also lead to sustainale agriculture. Sustainable water management should consider the environmental and equity issues and should cater to the needs of the poor and underprivileged who are generally marginal and small farmers.

6. References

Abu-Zeid, Mahmoud (2001), "Water pricing in Irrigated Agriculture", *Water Resources Development*, Vol.17, No.4.

---

[6] As no government tube-wells are functional and no credit is given to install new tube-wells.

Bhatia, Bela (1992), "Lush Fields and Perched Throats: Political Economy of Groundwater in Gujarat", *Economic and Political Weekly*, Vol.27, No.51-52, December 19.

Dhawan, B.D. (1982), "Development of Tube well Irrigation in India", Agricole Publishing Academy, New Delhi.

Dhawan, B.D. (1990), "Studies in Minor Irrigation: With Special Reference to Groundwater", Commonwealth Publications, New Delhi.

Dubash, N. K. (2002), "Tube well Capitalism: and Groundwater Development an Agrarian Change in Gujarat", Oxford University Press, New Delhi.

Gill, Kanwaljit & S.S., Gill (1990), "Agricultural Development and Industrialization in Punjab", *Economic and Political Weekly*, Vol.39, No.13, Nov 10.

Janakarajan, S. (1993), "Economic and Social Implications of Groundwater Irrigation: Some Evidence from South India", *Indian Journal of Agricultural Economics,* Vol.48, No.1.

Janakarajan, S. and Marcus, Moench (2006), "Are Wells a Potential Threat to Farmers' Well-being? Case of Deteriorating Groundwater Irrigation in Tamil Nadu", *Economic and Political Weekly*, Vol.41, No.37, 16 – 22 September.

Jasveen, Jairath (1985), "Private Tubewell Utilization in Punjab: A Study of Cost and efficiency", *Economic and Political Weekly*, Vol.20, No.40, October 5.

Moench, Marcus H. (2000), "India's Groundwater Challenge", *Seminar*, No.486, February.

Moench, Marcus H., (1992), "Chasing the Water Table: Equity and Sustainability in Groundwater Management", *Economic and Political Weekly*, Vol.27, No.51-52.

Nagraj, N. and Chandrakanth, M.G. (1997), "Intra and Inter Generational Equity Effects of Irrigation Well failures", *Economic and Political Weekly*, Vol.32, No.13.

Pant, Niranjan (Ed) (1984), "Productivity and Equity in Irrigation Systems", Ashish Publishing House, New Delhi.

Sarkar, Anindita (2009), "Sustainability Status of Rice-Wheat Cropping Pattern in Punjab: A Comparative Analysis of Different Irrigation Systems" *Environment, Development & Sustainability,* Volume 11, No. 4, Pp. 751 – 763.

Sarkar, Anindita (2011) "Socio-Economic Implications of Depleting Groundwater Resource in Punjab: A Comparative Analysis of Different Irrigation Systems", *Economic and Political Weekly,* Volume 46, No. 7, Pp. 59 – 66.

Shah, Tushaar (1993), "Groundwater Markets and Irrigation Development: Political Economy and Practical Policy", Oxford University Press, New Delhi.

Shah, T. (1988), "Transforming Groundwater Markets in Powerful Instruments of Small Farmers Development: Lessons from Punjab, Uttar Pradesh and Gujarat", Overseas Development Institute, London.

Shah, T. and K.V. Raju (1987), "Working of Groundwater Markets in Andhra Pradesh and Gujarat: Results of Two Village Studies", *Economic and Political Weekly*, Vol.22, No.6, February7.

Shah, Tushaar (1998), "Water against Poverty: Livelihood-Oriented Water Resource Management", *Water Nepal,* Vol.6, No.1.

Siddhu, H.S. (2002), "Crisis in Agrarian Economy in Punjab Some Urgent Steps", *Economic and Political Weekly*, Vol.37, No.18, July 27.

Singh, Chhatrapati (ed.) (1992), "*Water Law in India*", Indian Law Institute, New Delhi

Singh, Dalbir (2002), "Groundwater Markets in Fragile Environments: Key Issues in Sustainability", *Indian Journal of Agricultural Economics,* Vol.57, No.2.

2

Irrigation Water: Alternative Pricing Schemes Under Uncertain Climatic Conditions

Gabriele Dono and Luca Giraldo
University of Tuscia, Viterbo
Italy

1. Introduction

The European Water Framework Directive (European Union, 2000; herein, WFD) aims to protect the environmental quality of water and encourage its efficient use. The EU member states are required to implement effective water-management systems and appropriate pricing methods that ensure the adequate recovery of water costs. These directive also relates to the pricing of water for agriculture. However, a general framework specific methodologies used by each country to establish water tariffs is not yet available.

Furthermore, it appears that numerous exceptional rules of contexts prevent the adoption of uniform pricing guidelines even within individual countries (OECD, 2010).

In the past decade, various studies have focussed on the pricing of irrigation water. Albiac and Dinar (Albiac & Dinar, 2009) published an up-to-date review of approaches to the regulation of non-point-source pollution and irrigation technology as a means of achieving water conservation, and Molle and Berkoff (2007) performed a thorough analysis of pricing policies worldwide, touching on multiple aspects related to water policy reform, primarily in developing countries. Tsur and others (Tsur et al., 2004) presented a similarly wide-ranging analysis. Most of these studies based their conclusions on the results of numerical modelling and generally did not consider the uncertainties that farmers face in making decisions (Bazzani et al., 2005; Riesgo & Gómez-Limón, 2006; Bartolini et al., 2007; Berbel et al., 2007; Semaan et al., 2007; Dono, et al., 2010). However, uncertainty related to climate change is an important aspect of decision-making in the context of the management of agro-ecosystems and agricultural production. In this regard, process-based crop models, such as Environmental Policy Integrated Climate (EPIC) (Williams et al., 1989), have been widely used to simulate crop response to changing climate, addressing the problem of assessing the reliability of model-based estimates (Niu et al., 2009).

Climate change related to the atmospheric accumulation of greenhouse gases has the potential to affect regional water supplies (IPCC, 2007). In particular, the long-term scenarios calculated by most global and regional climate models depict a greater reduction in precipitation with decreasing latitude in the Mediterranean area (Meehl et al., 2007). This result is important because reduced water availability could result in heavily reduced net returns for farmers (Elbakidze, 2006).

There are various sources of uncertainty in climate change simulations (Raisanen, 2007), including those associated with the nature of the direct relationships between climate variability and water resources, given the strong influence on such relationships of land cover (Beguería et al., 2003; García-Ruiz et al., 2008) and water-management strategies (López-Moreno et al., 2007). The main problems for irrigation reservoirs are that they must be filled at the beginning of the irrigation season, whereas the filling season is characterized by a large uncertainty. Consequently, the management regimen of the reservoir, and even the pricing of its water resources, must be adjusted to the variable conditions of inflow.

2. Aim of the study

The present study assesses the economic effects and influence on water usage of two different methods for pricing irrigation water under conditions of uncertainty regarding the accumulation of water in a reservoir used for irrigation. For this purpose, several simulations are performed using a Discrete Stochastic Programming (DSP) model (Cocks, 1968; Rae, 1971a, 1971b; Apland et al., 1993; Calatrava et al., 2005; Iglesias et al., 2007). This type of model can be used to analyse some of the uncertainty aspects related to climate change (CC) because it describes the choices open to farmers during periods (stages) in which uncertainty regarding the state of nature influences their economic outcomes. The DSP model employed in this study represents a decision-making process based on two decisional stages and three states of nature, reflecting different levels of water accumulation in the reservoir (Jacquet et al., 1997; Hardaker et al., 2007; Dono & Mazzapicchio, 2010).

The model describes the irrigated agriculture of an area in North-Western Sardinia where water stored in a local reservoir is distributed to farmers by a water user association (WUA). Simulations are executed to evaluate the performances of the different water-pricing methods when the conditions of uncertainty regarding water accumulation in the dam are exacerbated by the effect of climate change on winter rainfall[1]. In fact, the model simulations are first executed in a present-day scenario that reproduces the conditions of rainfall and water accumulation in the dam during 2004[2]. The model is then run in a scenario of the near future, which is obtained by projecting to 2015 the rainfall trends of the last 40 years[3].

Among the various productive and economic impacts of the methods for water pricing that the WUA may apply, particular attention is paid to examining the changes in the extraction of groundwater from private wells in the various scenarios. This resource is used by farmers

[1] Rainfall is most abundant in winter, making this season the most important in determining the level of water accumulation in the dam.

[2] The present-day scenario focuses on 2004 because a detailed sequence of aerial photographs, showing land use in northwest Sardinia throughout the agricultural season, is available for this year, courtesy of the MONIDRI research project (Dono et al. 2008). These photographs enable us to evaluate the ability of the model to replicate the choices of farmers in terms of soil cultivation.

[3] We chose a near-term future scenario because the Italian agricultural policy barely extends beyond 2013, given the upcoming implementation of the Common Agricultural Policy. The climate scenario for this period will be crucial for farmers in terms of deciding to adhere to the RDP measures that support adaptation strategies to climate change. In addition, extrapolating trends to a longer-term climate results in greater uncertain regarding the quality of the climate scenario. Finally, a longer-term scenario would increase the likelihood that the farm typologies and production technologies considered in this study would have become completely obsolete.

to supplement dam water, and its over-extraction is a key issue of environmental protection in the Mediterranean context.

3. Background

3.1 Payment schemes

In Italy, irrigation water is distributed by local associations of farmers (WUA) that 'water storage and distribution facilities developed mainly using public funding. In line with the guidelines of the WFD, Italian WUAs charge the associated farmers for the operating costs of water distribution, the maintenance costs of water networks, and the fees paid to local authorities, representing the opportunity costs of water and the environmental costs of providing the water. This set of items is herein referred to as the cost of water distribution (WDC, Water Distribution Cost). In most cases, the water storage and distribution facilities were built with public money, meaning that their long-term costs (depreciation and interest) are not included in the budgets of the WUAs, which only manage the water distribution service. Consequently, these costs are not included in farmers' payments to the WUA for irrigation costs. Note that there is a recent trend for farmers to co-finance investments in irrigation infrastructure, in which case the farmers also bear the long-term costs in proportion to their participation.

WUAs adopt various methods for charging WDC, with the most widely used being a fee that is paid per irrigated hectare. Some WUAs levy a two-stage fee (binomial system).

The per-hectare fee has traditionally been the most widely adopted method in Italy because it is the simplest to manage in terms of charging farmers. In fact, WUAs compute WDC at the end of the irrigation campaign and divide it by the amount of farmland that water was supplied to by the collective irrigation network, regardless of whether the land was irrigated; consequently, this approach bears no relation to the amount of water used by farmers.

The two-stage system comprises a *basic payment* and a *water payment*. The *water payment*, directly or indirectly linked to water use, is computed by multiplying the unit price of water by the amount of water used by farms. *Water payments* that are directly linked to water use are calculated based on readings from water meters installed at farm gates, while those that are indirectly linked to water use are calculated by estimating the water needs (per hectare) for each irrigated crop. The unit price of water is usually defined before the beginning of the irrigation season and is generally set below the expected average WDC. Farmers are then asked for a *basic payment* which covers general and maintenance costs and that is usually charged to individual farms according to the area of land equipped with the collective irrigation network. The *water payment* component of this two-stage system can be calculated using two different methods.

A VPM (Volumetric Payment Method) approach is used in the case that water meters are installed and functioning on every farm (as this enables water use to be monitored). This approach does not usually apply when water is delivered to the farm gate by gravity-fed canal networks. National and Regional Governments commonly provide financial support to encourage a switch from canal to pipeline systems and to install farm-gate meters as part of collective networks. This financial support aims at reducing water losses from the network and providing a better service to farmers, but also at metering water supplied to farms and encouraging the switch to VPMs.

Alternatively, *water payments* are calculated using an Area-Based Pricing Method (ABM), which estimates the unitary irrigation requirements for each irrigated crop (i.e., crop-based charges). Some WUAs calculate large, accurate sets of estimates that vary according to crop type, irrigation technology, soil characteristics and climatic conditions. In contrast, other WUAs refer to broad groups of crops with different unitary irrigation requirements, although this approach yields only a rough estimate of farm water use. In the case that an ABM is employed, farmers must apply to the WUA for water by reporting their irrigation plan at the beginning of the season. The WUA then checks if the actual extent of irrigated crops is consistent with the irrigation plan (to prevent the avoidance of payments in the case that the plans show fewer crops than actually cultivated). In the event of severe drought, during which time farmers are forced to leave fields fallow, payments are calculated based on the actual extent of irrigated crops, not solely on the cultivation plan presented beforehand.

ABMs are based on irrigated acreage and the water needs of crops, irrespective of whether the water comes from a WUA network or from farm wells, thereby generating an indirect charging effect on groundwater. VPM is widely supported in technical and political debates because it directly links water payments to the amount of water delivered to farmers. However, for both pricing models, water charges are set by WUAs in order to recover the WDC. The use of the average cost in these calculations deviates from the prescription that a fully *efficient* allocation scheme for a scarce resource such as water should be based on balancing the marginal net benefits of its uses (Perman *et al.*, 2003). However, these methods of charging farmers, even if economically imperfect, are easily manageable by WUAs.

3.2 Study area

The study area covers the Cuga River basin in the Sassari district, northwest Sardinia (Italy), comprising 34,492 ha of farmland (Figure 1). On 21,043 ha of this area, around 2,900 farms receive water from the Nurra WUA, distributing the surface water stored in two man-made lakes, Cuga (30 million m^3) and Temo (54 million m^3).

The WUA distributes only surface water: groundwater is managed by farmers as a private asset. In this system, the water stored in the two lakes is shared between urban and farm uses. In the case of a water shortage, urban uses are given priority and farmers respond by using water from private wells, if available.

Surface water is distributed via two interconnected network systems that differ in altitude (i.e., for low and high land). For lowland areas, water from the two lakes is directly introduced into pipelines and distributed by gravity. For highland areas, water is first pumped into gathering basins located at a relatively high altitude, from where it flows downward under gravity through a network of pipelines. In 2004, the two systems carried similar volumes of water. The water fees paid by farmers are aimed at recovering the WDC incurred by the WUA. Since 2001, the pricing method has been VPM, whereby farmers pay 0.0301 €/m^3 (in 2004) as a *water payment* for the water they use, measured via farm-gate meters installed at each farm of the WUA. Before 2001, the Nurra WUA adopted an ABM based on per-hectare estimated water use for three different groups of crops (Table 1)[4].

[4] In the study area, water meters were installed at farm gates with a financial contribution from National and Regional Governments.

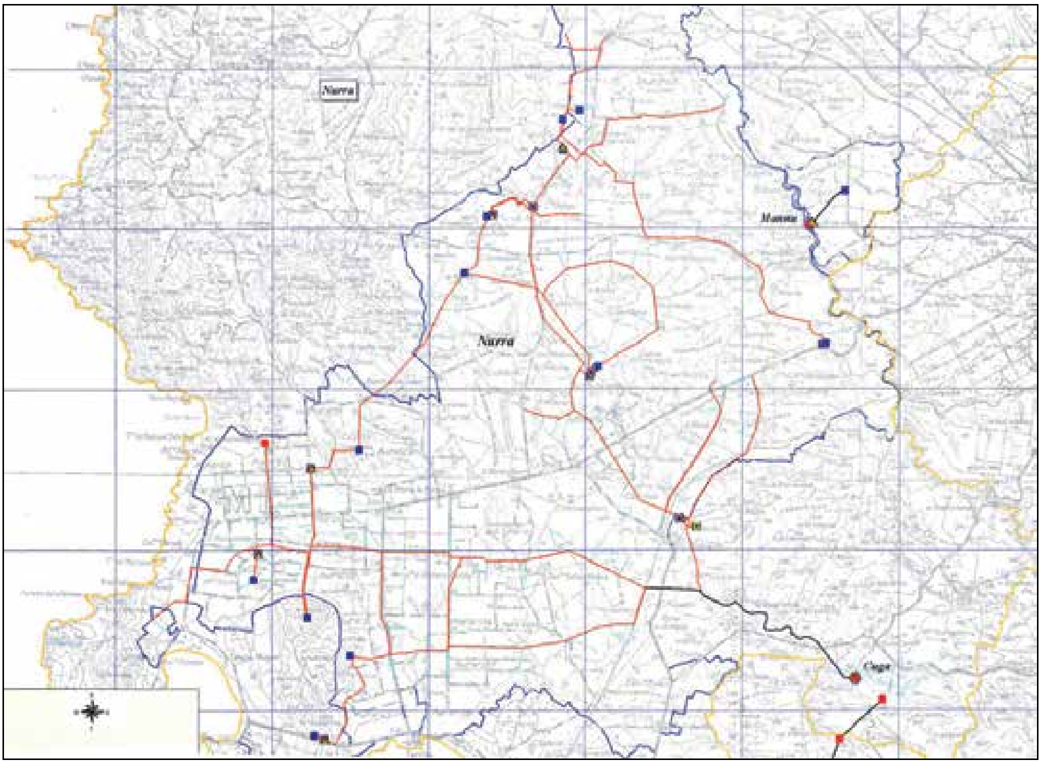


Fig. 1. WUA area of Nurra, North-Western Sardinia (Italy). Blue lines are the WUA boundaries; black line is the main channel from the reservoir to the pipeline network; redis the pipeline network.

	Areas served by the WUA					Areas *not* served by the WUA				
	Well	No. of farms	Ha per farm	Cattle (heads)	Sheep (heads)	Well	No. of farms	Ha per farm	Cattle (heads)	Sheep (heads)
Cattle, L**		2	532.4	1,558	-			-	-	-
Cattle, S		5	37.6	280	-	w	27	12.6	1,026	-
Crops, L	w*	139	66.1	-	-	w	52	55.8	-	-
Crops, M	w	28	10.2	-	-	w	148	7.7	-	-
Crops, S		1,509	0.7	-	-	w	540	0.9	-	-
Olive, M	w	33	12.3	-	-	w	25	13.4	-	-
Olive, S		543	0.8	-	-	w	542	1.0	-	-
Horticultural, M	w	41	14.8	-	-	w	8	8.7	-	-
Horticultural, S	w	49	2.8	-	-	w	10	2.1	-	-
Sheep, M	w	34	64.1	-	57,578	w	33	76.3	-	14,398
Sheep, S	w	94	26.1	-	40,353	w	45	34.4	-	21,273
Vineyards, L	w	1	693.0	-	-			-	-	-
Vineyards, M	w	136	2.7	-	-	w	44	2.0	-	-

** Farm possesses a private well.*
*** L, Large; M, Medium; S, Small.*

Table 1. Farm typologies in the areas served and not served by the Nurra WUA.

There are no official data on the extraction of water from wells; however, the WUA's engineers have estimated that the annual withdrawal of groundwater is between 2.5 and 4 million m^3, depending on how much water from the dams is provided for agricultural use. The number of wells owned by farms, as well as their location and technical features, has been identified from Agricultural Census data and from data compiled as part of the RIADE Research Project, jointly run by ENEA (National Agency for New Technology, Energy and Sustainable Economic Development, Italy) and the University of Sassari (Italy) (Dono et al., 2008). These data reveal that farms use approximately 107 wells in the area.

The agricultural sector of this territory is represented by a regional DSP model consisting of 24 blocks describing the most relevant farming systems. Each farming system, called a macro-farm (with reference to the block in the model), represents a group of farms that are homogeneous in terms of size (cultivated land and number of livestock head), production patterns, labour availability, presence of wells and location within the study area (Table 1). These macro-farms are defined using data from field surveys, the 2001 Agricultural Census and records of the European FADN (Farm Accountancy Data Network). The availability of multiple sources of farm data enabled us to consider economic characteristics (e.g., budget, net profit and performance indexes) in defining macro-farms. Thirteen of the macro-farms are located in the zone to which the WUA delivers water; 11 are located outside of this zone, where farms rely solely on water from privately owned wells or practice rain-fed agriculture. Note that the production of some of these typologies is not considered as typically Mediterranean, such as intensive dairy production and the associated cultivation of irrigated crops as forage.

In the mathematical programming model, production technologies for crops and livestock breeding are accurately defined based on the main activities observed in the study area. In particular, the use of water by crops is defined according to the employed irrigation techniques. Drip irrigation techniques, used for horticultural and tree crops, are represented in the model, whereas flood irrigation is not because this technology is not employed in the area. Farm typologies and production technologies that characterize the agricultural sector of the area were reconstructed as part of the MONIDRI Research Project, run by INEA (National Institute for Agricultural Economics, Italy) (Dono et al., 2008).

4. Methods

4.1 DSP models (general characteristics)

Discrete Stochastic Programming models (Cocks, 1968; Rae, 1971a, 1971b; Apland et al., 1993; Calatrava et al., 2005; Iglesias et al., 2007) can be used to analyse some of the uncertainty aspects related to CC. DSP models describe choices made by farmers during periods (stages) of uncertainty regarding conditions. Therefore, such models represent the decision process that prevails under typical agricultural conditions, where farmers are uncertain regarding which state of nature will prevail in the cropping season that is being planned, and it is only possible to estimate the probability distributions of the various states of nature. In this study, the DSP model represents a decision-making process based on two decisional stages and three states of nature (Jacquet et al., 1997; Hardaker et al., 2007), where farmers face uncertainty regarding the wintertime accumulation of water in a dam. In the literature, two-stage DSP models have considered various states of nature in the second stage. Jacquet and others (Jacquet et al., 1997) used four states of nature associated with annual rainfall, and Hardaker and others (Hardaker et al., 2004) represented the planning problems in dairy farming by referring to three levels of milk production. However, these authors did not justify the number of stages or the number of states of nature employed in the analyses, except for the need to simplify the problem as much as possible.

The first of the two stages of the DSP model proposed in this paper represents an autumnal period of choice, when farmers establish fields for winter crops. The limited irrigation needs of these cultivations can be satisfied by extraction from farm wells, and hence they are not directly influenced by uncertainty about water availability from the dam. However, when defining the area for winter crops, farmers also establish the surface to be left for spring crops. In contrast to winter crops, the irrigation needs of spring crops are substantial and can only be met by using water accumulated in the dam, whose availability is uncertain. In this way, uncertainty about water availability during the spring period influences the farmers' choices in the autumn period.

The second stage of the DSP model concerns the spring–summer period of choice. At that time, winter accumulation of water in the dam has already occurred, and farms can choose the area to be allocated to each spring crop with certainty. However, during this period farmers can only cultivate the area left unused from the first stage, when uncertainty about water levels in the dam might have produced choices that, in spring, turn out to be sub-optimal. This uncertainty is expressed by a probability distribution function of the level of water accumulation in the dam. The distribution is then discretized to yield three states of water accumulation (high, medium and low) along with their associated probability of realization.

The DSP model represents the influence of this uncertainty on the decision-making processes of farmers. According to this model, the farmer knows that different results may arise in planning the use of resources based on a certain state of nature. In particular, with three states of nature, three different results may occur. One is optimal, when the state of nature assumed by the farmer occurs as expected. The other two results are sub-optimal, where the farmer plans resource allocation based on a certain state of nature, but one of the other two states occurs, resulting in reduced income compared with the optimal outcome. The probabilities of these three results are the probabilities of the respective states of nature. The DSP represents the decision-making processes of the farmer who, based on these data, calculates the expected income of all the various outcomes (obtained by weighting the incomes from the three results with the probabilities of the respective states of nature) and adopts the solution that yields the higher expected income. Accordingly, the farmer adopts the use of resources generated by a weighted average of the three solutions.

Note that a solution that also weights the sub-optimal results may represent the outcome of precautionary behaviour of farmers who try to counter programming errors generated by relying on a given state of nature that ultimately does not occur. Also note that this average of DSP outcomes is different from the average of LP (Linear Programming) model outcomes under low, medium and high water-availability scenarios. Indeed, LP results are optimal to the relative water-availability state, considered in the LP model to be known with certainty. In contrast, DSP outcomes are sub-optimal when a state is planned but does not eventuate, meaning that average income levels are smaller than the analogous income levels in the LP model. This difference can be considered as the cost of uncertainty.

A major limitation of this approach may be that the farmer represented by the DSP model is risk-neutral; thus, the lower resulting income represents the cost of making optimal choices under conditions of uncertainty, but does not consider the cost of the farmer's attitude towards risk (risk aversion). Another limitation may be that we considered only one factor of uncertainty, whereas the farmer's decision-making process is affected by multiple uncertain factors that overlap. The future development of this analysis would be as a multi-stage DSP model with a larger number of uncertainty factors. However, with increasing number of stages and factors, the model becomes difficult to handle; consequently, it is crucial to identify the most relevant elements.

4.2 DSP model (technical characteristics)

As mentioned above, the DSP model used in this analysis is articulated in blocks of farm typologies. Each block refers to a macro-farm that represents a group of farms in the study area. The macro-farms differ in terms of structural characteristics (quality and availability of fixed resources in the short term), farming system and location. The optimisation problem involves maximising the sum of the stochastic objective functions of single macro-farms (expected gross margins), subject to all of the farming restraints (specific as well as territorial). Expected gross margins for each state of nature are given by the sum of two elements: one obtained from activities started in the first stage, and the other obtained from activities of the second stage. This DSP model can be mathematically formalised as follows:

Objective function:

$$\underset{X}{Max} \quad Z = GI_1 * X_1 + P_K * GI_2 * X_{2,K} \tag{1}$$

Subject to:

$$A_1 * X_1 + A_2 * X_{2,K} \le b_K \quad \forall \mathrm{K} \tag{2}$$

$$X_1, \ldots, X_{2,K} \ge 0 \quad \forall \mathrm{K} \tag{3}$$

where Z is the total gross margin, X_1 is the vector of first-stage activities, $X_{2,K}$ is the matrix of second-stage activities for each state of nature occurring in the second stage, P_K is the probability of occurrence of each state of nature, GI_1 and GI_2 are the vectors of unitary gross margins, A_1 and A_2 are the matrixes of technical coefficients, b_K is the vector of resource availability for each state of nature (here, only the availability of water has a different value for each state of nature; other resources have the same value), K is the state, and 1 and 2 are the stages. The variables of the model can be divided into three groups: crop, breeding and animal feeding; acquisition of external work; and activity related to the water resource.

Several groups of model constraints are defined. The first group refers to the expected availability of labour, land and water. Labour constraints are specified with reference to family labour and hired labour, permanent or temporary. Water constraints apply to both the reservoir water supplied by the WUA, as well as the groundwater, which can only be utilised based on the presence and technical characteristics of wells on the farms. The constraints on the expected availabilities of labour, land and water are specified for each month. Another set of constraints is concerned with agronomical practices as commonly adopted in the area to avoid declines in crop yields. Other constraints refer to Common Agricultural Policy systems to control production, such as production quotas and set-asides. Moreover, livestock breeding requires a balance between animal feeding needs and feed from crops or purchased on the market. In addition, constraints are imposed for specific farm typologies on the number of hectares of various trees growing and on the number of raised cattle or heads of sheep. These constraints are applied at different levels: some are specified at the farm level, such as the constraints on land use and on family and permanent labour, which cannot exceed the farm availability of these resources; others act at the area level, such as the constraint on the total irrigation water provided to farms, which cannot exceed the total water resources available to the WUA. Similarly, a constraint on temporary hired labour is specified at the area level. Finally, constraints on water availability are specified for each state of nature, for each of three scenarios regarding the distribution of water accumulation. Input and Produce Prices are defined as values that could be expected in 2004, based on the average of actualised values in the 3 preceding years. Similarly, agricultural policy conditions in 2004 are applied (Dono et al., 2008).

In essence, the basic approach of this study is to use a regional DSP model to estimate the impact of CC on production activity and income of farms in the area and to assess the performances of the various water-pricing methods under different climatic conditions. The stochastic expectations of water accumulation in the dam, which are included in the DSP model, are considered to be altered by CC that modifies the rainfall regime. The present-day (2004) probability distribution of water accumulation in the reservoir is estimated and used as a proxy for the stochastic expectation in the DSP model that reproduces the present conditions. This distribution is replaced with a future scenario probability function for rainfall and, hence, for the level of water accumulation in the dam. This future scenario is obtained by projecting historical rainfall data.

The next section describes the criteria used to reconstruct climate scenarios of winter precipitation and the resulting probability distributions for the accumulation of water in the dam, in the present and future.

4.3 Climatic scenarios

The present and future scenarios for water accumulation in the reservoir were reconstructed using the statistical correlation between rainfall amount and water storage in the dam, and by extending to the 2015 year the estimated trend of a 40-year rainfall series.

Estimation of the probability distribution for water accumulation in the reservoir was complicated by the fact that the Nurra WUA was only able to provide accurate monthly data for short periods in recent years. At the time of the MONIDRI research project, accurate records were only available for the years 1992–2003. Table 2 lists the annual values of water allocation obtained from these monthly data, showing that on average, potable use accounted for 40% of the available resource. In the years 1995, 2000 and 2002, the total amount of water available was insufficient to meet all the needs, and the Commissioner for Water Emergency limited the amount withdrawn for irrigation in favour of domestic usage, which had a major impact on farm incomes. During these years, the withdrawal for domestic use exceeded that for irrigation.

Water uses	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Irrigation	*43.5*	*33.4*	*31.6*	*2.3*	*23.2*	*39.1*	*10.4*	*17.6*	*2.4*	*27.8*	*12.4*	*26.6*
Potable	*10.3*	*11.2*	*11.3*	*10.9*	*12.8*	*12.7*	*13.2*	*14*	*14.3*	*20.4*	*19.7*	*8.1*

Table 2. Amount of water (million m^3) from Cuga Dam allocated to different uses in the period 1992–2003 (source: Nurra WUA).

The limited temporal coverage of this record of water use makes it statistically insufficient for estimating the probability distribution of states of water storage for the present scenario, and even more so for the future. In addition, hydrological models had not been developed for the study area for the appropriate transformation of long-period rainfall data in terms of water accumulation in the Cuga Dam. To overcome these limitations, a statistical relationship was estimated between rainfall amount and water accumulation level, and the parameters of this relationship were used to generate the probability distributions of water collection states. The following section describes the procedure for estimating the statistical relationship between rainfall regime and level of water accumulation in the reservoir. These estimated values are used to obtain the probability distribution of water level in the reservoir, for which low, medium and high states of accumulation were defined.

4.4 Assessment of climate change

The first step in the analysis was to examine the long-term trends in the rainfall regime that are believed to have influenced the accumulation of water in the Cuga Dam. Rainfall in the area was analysed using a 43-year series of monthly data (1961–2003) comprising a total of 516 observations. This analysis assumed an additive or multiplicative relationship between the components. The choice between additive or multiplicative decomposition methods was based on the degree of success achieved by their application (Spiegel, 1973). In this study, the multiplicative method yielded slightly better results than the additive decomposition. The analysis was therefore based on the assumption that the following multiplicative link exists among components:

$$X = T * S * C * \varepsilon \tag{4}$$

where X is the observed rainfall data as generated by trend T, seasonality S, cycle C and residual elements ε. The influence of these elements was decomposed. To estimate the trend, a linear function was used as follows:

$$\text{Rain} = \delta_0 + \delta_1 \text{T} + \varepsilon \tag{5}$$

where Rain is rainfall, T is time and δ_0 and δ_1 are the parameters of the function. Quadratic or exponential functions can also be used for estimating trends; the choice among the different structures is generally based on their statistical adaptation to the analysed series (Levine et al., 2000).

Seasonality (S), as a specific characteristic of each individual month, was obtained by first normalising the monthly data to the average for that year, and then computing from these values the median for each month in the observed range. We assumed the absence of a cycle (C) in climatic events of the study area, given the lack of clear physical phenomenon (e.g., a dominant atmospheric circulation pattern) linked to cyclic behaviour in the study area.

Finally, residuals were calculated by isolating the observed data from the climatic components of trend and seasonality, given that any cycle is assumed to be absent. Residuals usually depend solely on random and uncertain factors; i.e., they are stochastic elements that represent the variability of climate phenomena. Analysing the standard deviation of residuals can highlight the existence of temporal changes in the variability of climate phenomena, which is an important part of CC. This analysis can be developed by estimating a linear trend of the standard deviation of residuals, as follows:

$$\text{SDR} = \gamma_0 + \gamma_1 \text{T} + \varepsilon \tag{6}$$

where SDR is the standard deviation of residuals and γ_0 and γ_1 are the parameters of the function.

4.5 Statistical relation between rainfall regime and water accumulation in the Cuga Dam

Once the rainfall data had been examined and the presence of relevant trends highlighted, a statistical relationship was estimated to define the on water accumulation in the Cuga Dam. A linear regression model between rainfall (Rain) and water amount in the dam (Wa) was constructed based on the 144 monthly observations for the period 1992–2003. The estimated coefficients of this regression and the observed rainfall data were used to reproduce the entire series of data on water amount in the dam for the period 1961–2003. This procedure generated a sufficiently long series of data on water accumulation in the dam to be used when estimating the probability distribution of this variable.

In more detail, when estimating the statistical relationship between rainfall data and water accumulation level, a preliminary analysis of the data was performed to reveal (and eventually correct) the possible non-normality and non-stationarity characteristics of the series. A series is considered normal when the characteristics of symmetry and unimodality make it similar to the realisations of a normal random variable. A stationary process is a stochastic process whose joint density distribution does not change when shifted in time or space; as a result, parameters such as mean and variance (if they exist) also do not change over time or space. To satisfy the regression model hypothesis, data that do not show normality or stationarity characteristics must be standardised to obtain a stationary series, as follows:

standardisation:

$$X_{SAV_{i,j}} = \frac{X_{OBS_{i,j}} - \mu_i}{\sigma_i} \tag{7}$$

where $X_{SAVi,j}$ is the series of seasonally adjusted values, $X_{OBSi,j}$ is the series of observed values, μ_i is the monthly average of the values of the observed series, σ_i is the monthly standard deviation of the observed series, and i and j indicate the month and year, respectively.

Therefore, the standardised data were normalised by using a Box–Cox transformation:

normalisation:

$$X_{tras_{i,j}} = \begin{cases} \dfrac{(X_{SAV_{i,j}})^{\lambda} - 1}{\lambda} & for\ \lambda \neq 0 \\ \log(X_{SAV_{i,j}}) & for\ \lambda = 0 \end{cases} \tag{8}$$

where λ is determined by maximising the following log-likelihood function:

$$\ln L(\lambda, \bar{x}_{SAV}) = -\frac{n \cdot m}{2} \ln\left[\sum_{i=1}^{n}\sum_{j=1}^{m} \frac{(x_{SAV\,i,j}(\lambda) - \bar{x}_{SAV}(\lambda))^2}{n \cdot m}\right] + (\lambda - 1)\sum_{n}^{i=1}\sum_{j=1}^{m} \ln(x_{SAV\,i,j}) \tag{9}$$

and

$$\bar{x}_{SAV}(\lambda) = \begin{cases} \dfrac{1}{n \cdot m}\displaystyle\sum_{i=1}^{n}\sum_{j=1}^{m}(x_{SAV\,i,j})^{\lambda} & for\ \lambda \neq 0 \\ \dfrac{1}{n \cdot m}\displaystyle\sum_{i=1}^{n}\sum_{j=1}^{m}\ln(x_{SAV\,i,j}) & for\ \lambda = 0 \end{cases} \tag{10}$$

where n and m are respectively the number of months and years.

Hence, making use of standardised and normalised data on water amount in the dam (Wa_{tras}) and on rainfall ($Rain_{tras}$), we constructed the following model:

$$Wa_{tras} = \beta_0 + \beta_1 Rain_{tras\,(-1)} + \beta_2 Wa_{tras\,(-1)} + \varepsilon \tag{11}$$

Based on the coefficients of this model, Wa_{tras} values were first calculated for the period 1961–1991 and then transformed into water availability data (Wa) by applying the inverse Box–Cox transformation (inverse of normalisation) and the inverse standardisation adjustment.

4.6 Probability distribution of water accumulation in the dam

The inferred data on water accumulation levels for individual months during the period 1961–2003 were used to estimate density functions related to sub-periods within this interval. These functions were estimated on the basis of a dataset restricted to March values, because this month is the last before the start of the irrigation campaign. Consequently, the level of water accumulation in March is crucial for decisions made by farmers regarding the cultivation of irrigated and non-irrigated crops, and for decisions made by WUAs regarding water allocation to farms. The parameters of these density functions are estimated using the software @Risk, which uses a chi-square value (Goodness of Fit index) to select the function that best approximates the dataset. These parameters are the basic input for generating the stochastic expectations of farmers in the DSP model.

Probability values can be computed and incorporated into DSP models only for states of nature expressed as intervals and not as single values (Piccolo, 2000). To this end, based on water management in the area of interest, three accumulation states are considered as relevant to the use of reservoir water in the farm sector: high, medium and low. The first state is recognised as occurring in years when the dam contains abundant water, when no limits are imposed on water use for irrigation or other purposes. A state of medium accumulation is identified for years when the amount of collected water necessitates careful use, even if explicit measures of public rationing are not required. A state of low accumulation is recognised when major water emergencies occur and irrigation is limited by public authorities to ensure the availability of water for potable use. The boundaries between these states are defined based on their occurrence in 1992–2003. Specifically, the lower limit of the low accumulation state is taken as the minimum value of the series: 5.6 million cubic meters (Mm^3). The upper bound of this state is taken as the maximum value at which irrigation was publicly rationed to guarantee potable use (42.6 Mm^3). This latter value is also the lower bound of the medium state, whose upper limit (64.0 Mm^3) is defined based on symmetry about the average value of accumulation (53.3 Mm^3). The value of 64.0 Mm^3 is also the lower bound of the high accumulation state, whose upper limit is the maximum value of the series, 89.9 Mm^3. Different sub-periods during the interval 1961–2003 yield different distributions of water accumulation states, with different probabilities and average values for the three states. The parameters of these different functions can be used to generate stochastic expectations of water accumulation in the dam, as represented by the regional DSP model.

The dataset obtained using this adjustment to the regression results was used to estimate a first probability distribution function for the continuous, stochastic variable of water accumulation in the dam, based on data for the years 1984–2003; this represents the expectations of the present period. Similarly, 21 distributions were computed by progressively shifting the 20-year period forward, by 1 year at a time, from the period 1964–1983 to the period 1984–2003. The probability values for low, medium and high levels of water accumulation in the dam were computed for each of these distributions. Based on the result, linear trends of probability values for the three states of nature were estimated and projected to estimate data for the years 2004–2015 and to compute an analogous probability distribution for the 20-year period 1996–2015. The probability distributions obtained in this way for the years 1984–2003 and 1996–2015 were used to represent the stochastic expectations in the present and future, respectively.

4.7 Simulation scenarios

The baseline model of this study refers to the VPM, as applied by the Nurra WUA in 2004, when the *water payment* was set at 0.0301 €/m^3 for water delivered by the WUA distribution network and the *complementary payment* was charged to fully cover the WDC. With this pricing method, only the *water payment* directly affects farmers' water use. No charge for the use of groundwater is applied by the WUA.

Two other scenarios refer to ABM. In these cases, the farm payment for water consists of two components: the *water payment* is charged according to *estimates* of the water requirements of crops, multiplied by the water unitary price (0.0301 €/m^3), and the *complementary payment* is again charged to ensure that the WDC is fully recovered.

Two ABM scenarios are simulated (ABM-1 and ABM-2), referring to two different methods of estimating the water applied to each crop. In ABM-1, these estimates accurately reflect the irrigation requirements of every crop, whereas in ABM-2 the crops are clustered into classes that consider their *average* irrigation requirements[5]. This latter scenario considers the ABM practiced by the Nurra WUA until 2001, where the estimates of unitary irrigation requirements used in calculating the payments are not always consistent with the actual requirements of crops (Table 3)[6]. The main feature of ABMs is that the payment is charged regardless of the water source (i.e., surface water from the WUA or groundwater from private wells). Furthermore, all irrigated areas are supposedly charged by the WUA. Given that farmers pay according to the area under irrigation and that the price is set considering estimates of irrigation requirements, irrigation payments are affected by cropping patterns but not by the source of water.

I – (104.30€/ha)	II – (143.84 €/ha)	III – (179.77 €/ha)
Tomatoes in glasshouses	Ryegrass	Artichoke
Watermelon	Alfalfa	
Melon	Clover	
Olive trees	Corn	
Vineyard	Open field Tomatoes	
Peach trees		

Table 3. Payment classes in the Nurra WUA (based on the parameters applied in 2001)

5. Results

First, we present the temporal changes in rainfall patterns over the past 40 years, and then describe the outcomes obtained by estimating a statistical relationship between the rainfall regime and level of water accumulation in the dam. Subsequently, the levels and respective probability values for states of water accumulation in the dam are reported for each of the three scenarios. Finally, we present the economic and productive outcomes of the DSP models.

5.1 Precipitation time series

The linear trend of monthly rainfall reveals a decrease in the area, indicated by the value of the regression coefficient in relation to time (δ_1) (Table 4). In addition, the linear trend in the monthly variability of the standard deviations of residuals reveals an increase residuals, as indicated by the regression coefficient of the same standard deviations of residuals in relation to time (γ_1).

5.2 The regression model

A preliminary analysis of the data reveals a statistically significant autocorrelation in the Wa series and cross-correlation between the Wa and Rain series. The data were then

[5] Some WUAs chose this last option to reduce their administrative burden or because of political reasons, such as considering the relative contributions of certain crops in terms of farm employment or income.

[6] For instance, clover and alfalfa in the second class (Table 3) pay less than artichoke in the third class, yet the water needs of the former are approximately twice those of the latter. This favourable treatment is justified by WUAs because alfalfa and clover crops are relevant to the cow- and sheep-milk sectors, which are considered to be important for the economy of the entire area.

standardised and normalised, and new time series of the amount of water in the dam (Wa_{tras}) and rainfall ($Rain_{tras}$) were used to estimate the model (11).

	Coefficient	Estimate	T-stat	P value
Rainfall	δ_0	55.645	13.6477	0.000
	δ_1	-0.0381	-2.7904	0.000
Standard deviation of residuals	γ_0	131.07	3.2885	0.000
	γ_1	2.74	1.6568	0.100

Table 4. General trends of rainfall and of the standard deviation of residuals.

Good statistical results were obtained from the regression: the coefficients have the expected signs and are statistically significant, and high R^2 values indicate that more than 95% of the variability in Wa_{tras} is explained by the model (see Table 5).

Coefficient	Estimate	T-stat	P-value
β0	-0.3149	4.5442	0.000
β 1	0.5828	5.3247	0.000
β 2	0.9694	54.6706	0.000
R^2	0.9555	F	1501.44
Adj-R^2	0.9548	p (F≤f)	0.000

Table 5. Results of the regression model for the dependent variable Wa_{tras}.

Based on these coefficients, Wa_{tras} values were calculated for the period 1961–1991 and were then transformed to water availability data (Wa) by applying the inverse Box–Cox transformation (inverse of normalisation) and the inverse standardisation adjustment.

5.3 The density distribution of water accumulation

The dataset obtained from this adjustment of the regression results was used to estimate the density functions of water accumulation in the dam for the period 1984–2003. The best estimate was a triangular function with a chi-square value of 0.400 and a p-value of 0.9402. With k (number of bins) = 4 (3 degrees of freedom), the null hypothesis is accepted (i.e., that this is the best possible function for representing the data). Once the boundaries of the low, medium and high accumulation states were defined based on data for the period 1992–2003, the respective probabilities were computed, yielding values of 27.3%, 40.7% and 32.0%, respectively.

Next, the density distribution values for the future scenario were determined. To this end, 21 distributions were computed by progressively shifting the 20-year window, 1 year at a time, from 1964–1983 to 1984–2003. The probability values for low, medium and high levels of water accumulation in the dam were computed, yielding a progressive increase in the degree of variability, especially for periods more recent than 1976–1995. Based on these data, linear trends of probability values for the three states of nature were estimated and projected to obtain an analogous distribution for 1996–2015, yielding values of 38.8%, 13.7% and 47.5% for the states of low, medium and high water accumulation in the dam, respectively.

Once the total accumulation levels and respective probabilities had been defined for the two scenarios, the respective availabilities of water for irrigation were also defined. To this end, the data supplied by the WUA for the years 1992–2003 were used to infer the level of water accumulation in the dam and the percentage of water allocated to irrigation for each of the three states of nature. These percentages were used to define the amount of water accumulated in the dam that farmers could expect to be allocated to agriculture in each state of nature.

As a side analysis, an analogous distribution based on data for the period 1964–1983 was computed with the same boundaries for water collection states, yielding probability values of 0.0%, 99.7% and 0.3% for the low, medium and high levels, respectively. Compared with the previous scenario, these outcomes reveal that water accumulation in the dam during the 1960s and 1970s was characterised by a smaller variability than in present scenario. This result is consistent with the finding of a temporal increase in rainfall variability, as obtained by analysing the standard deviation of residuals (see Table 4).

5.4 The DSP models

The DSP simulation models employed in this study were solved using the program GAMS (General Algebraic Modelling System; Brooke et al., 1996). The baseline of this study is the average of the outcomes related to the three states of nature in the present scenario, weighted by the respective probabilities. The baseline is evaluated by comparing its average weighted outcome regarding land use to the actual pattern determined from remote sensing data and field data approved by the WUA (Dono et al., 2008). The similarity between the patterns is assessed by the Finger–Kreinin index, which compares the respective percentages of total land occupied by each group of crops, selects the lower value among them and sums the figures (Finger and Kreinin, 1979). The more similar that two series are, the higher the sum of the lower values, which yields a value of 100% for identical series. A high degree of similarity is obtained in this study between DSP outcome and the actual land use, with the value of the similarity index being 91.9%. The baseline model is therefore considered to adequately reproduce the observed choices of farmers and is therefore useful for providing insights into farmers' possible adjustments in the case of changing economic or climatic conditions[7].

At this point, we can discuss the results obtained with different pricing methods for the water distributed by the WUA, in the context of the present and future climate. Table 6 lists

[7] An analogous linear programming model (LP) was constructed, differing only in the condition of irrigation water availability, which was defined as the average water level in the dam over the previous 5 years. By considering uncertainty, the DSP model yields better results in reproducing agricultural activities; in fact, the Finger–Kreinin similarity index has a lower value (90.2) in the LP model.

the key financial results for the entire area in which the WUA distributes water from the reservoir.

Outside of this area, agriculture is not irrigated and is not affected by the water pricing system of the dam or changes in the volume of water in the reservoir. Table 6 lists the total revenues, indicating the portion of product sales, the main items of variable costs and gross margin. Fixed costs have been estimated for the various farm typologies, enabling the calculation of their net incomes; these are aggregated to yield the entire area value. Table 6 lists all of these values, expressed in thousands of euros and in percentage change from the baseline (in this VPM).

	Absolute value ('000 €)						% variations from the Baseline				
	present	Present		future			present		future		
	VPM	ABM		VPM	ABM		ABM		VPM	ABM	
	Baseline	1	2		1	2	1	2		1	2
Revenue	73,892	73,892	73,906	73,713	73,713	73,644	0.0	0.0	-0.2	-0.2	-0.3
Sales	64,667	64,667	64,68	64,557	64,557	64,478	0.0	0.0	-0.2	-0.2	-0.3
Costs	19,109	19,151	19,218	19,431	19,483	19,505	0.6	0.2	1.7	2.0	2.1
Feeding cost	*430*	*430*	*430*	*723*	*723*	*723*	*0.0*	*0.0*	*68.2*	*68.2*	*68.2*
Labour cost	*2,133*	*2,133*	*2,134*	*2,34*	*2,34*	*2,321*	*0.1*	*0.0*	*9.7*	*9.7*	*8.8*
WUA cost	*341*	*407*	*461*	*289*	*362*	*450*	*19*	*35*	*-15*	*6*	*32*
Drawing cost	*82*	*58*	*58*	*88*	*67*	*66*	*-29.7*	*-29.7*	*6.8*	*-18.7*	*-19.1*
Irrigation Equip.	*1,381*	*1,381*	*1,381*	*1,379*	*1,379*	*1,365*	*0.0*	*0.0*	*-0.1*	*-0.1*	*-1.2*
Other costs	*14,06*	*13,928*	*13,831*	*14,034*	*13,888*	*13,681*	*-0.9*	*-1.6*	*-0.2*	*-1.2*	*-2.7*
Gross Margin	54,783	54,742	54,688	54,283	54,231	54,139	-0.2	-0.1	-0.9	-1.0	-1.2
Net Income[8]	32,627	32,532	32,586	32,127	31,983	32,075	-0.3	-0.1	-1.5	-2.0	-1.7

Table 6. Economic results for the entire area.

These data show that the transition from VPM to the ABMs generates a very small change in income in the present climate scenario. However, a significant change in cost structure emerges, with a strong reduction in expenses for the extraction of water from wells and an increase in the irrigation payments to the WUA. This change occurs because the two ABMs are based on irrigated acreage and the water needs of crops, irrespective of whether the water is derived from the WUA network or from farm wells, thereby generating an indirect pricing of groundwater. Consequently, the two ABMs encourage farmers to reduce the use of groundwater that is only applied in cases where irrigation is necessary but the WUA irrigation season has yet to open, or during the summer periods when the water resources of the WUA do not meet the general water demand of the area.

[8] Net income is obtained based on estimates of fixed costs coming from European FADN database.

The transition to the future climate scenario results in a more pronounced change in cost structure. The greater variability in water accumulation in the reservoir generates a greater reduction in total income, which also affects the system based on VPM. With this method of charging, there is an increase in the cost of drawing groundwater and a reduction in irrigation payments to the WUA. At the same time, there is an increase in the cost of purchasing feed and forage that can no longer be sufficiently produced locally under the new scenario of expectations regarding the availability of water in the reservoir. Of note, the use of ABMs yields the same increase in costs as when using VPM. However, these last two methods of water pricing are completely different from VPM in terms of the effect on other cost items. As in the present scenario, a reduction in expenses occurs with the extraction of water from wells, with a parallel increase in irrigation payments to the WUA. These variations are less pronounced than in the present scenario because the expectation of a greater variability in the future accumulation of water in the reservoir prevents a more significant reduction in the use of groundwater.

Table 8 lists the net incomes of the farm typologies in the study area for each scenario, grouped by product specialization. These data show that the farms involved mainly in the production of crops (cereals, oilseeds and protein crops, and also forage and pasture) make the greatest contribution (30%) to the agricultural income of the territory, followed by vineyards and to a much lesser degree the sheep farms and the other typologies.

In the case of ABM-2, the horticultural farms show a marked increase in income, which is not seen in the case of ABM-1. This result indicates that estimates of the water needs of the WUA in ABM-2 favour some vegetables grown by horticultural farms.

Farm Typology	Absolute value ('000 €)						% variations on the baseline				
	present	Present		future			present		future		
	VPM	ABM		VPM	ABM		ABM		VPM	ABM	
	Baseline	1	2		1	2	1	2		1	2
Cattle	1,363	1,364	1,365	1,207	1,208	1,206	0.1	0.1	-11.5	-11.4	-11.5
Arable	13,738	13,691	13,634	13,381	13,339	13,322	-0.3	-0.8	-2.6	-2.9	-3
Olive	3,525	3,54	3,545	3,511	3,511	3,529	0.4	0.6	-0.4	-0.4	0.1
Vegetable	982	982	1,048	1,050	1,050	1,029	0	6.7	6.9	6.9	4.7
Sheep	2,691	2,683	2,684	2,657	2,65	2,649	-0.3	-0.2	-1.2	-1.5	-1.5
Vineyard	9,36	9,356	9,287	9,353	9,348	9,279	0	-0.8	-0.1	-0.1	-0.9
Total	31,658	31,617	31,563	31,158	31,106	31,014	-0.1	-0.3	-1.6	-1.7	-2

Table 7. Net income of farming typologies.

However, the most interesting aspect of this table is the effect of the transition to the future scenario. The mean changes emerge as the result of very different changes among the typologies, with a collapse in the incomes of dairy farms and an appreciable increase in the income of vegetable growers. The choice of pricing system of irrigation water has little influence on the effect of increased variability in water accumulation in the dam.

The VPM scheme encourages farmers to meet their water requirements with minimum cost. Consequently, farmers with wells tend to draw water until it remains cheaper than the WUA *water payment*. Thus, the VPM scheme results in increased groundwater extraction. Under the ABM scenarios for the present, in contrast, farmers only draw groundwater from wells if the WUA is unable to supply water, either because of a demand pick or a request coming off the irrigation season. Otherwise, farmers are inclined to use the WUA water as much as possible, because such behaviour does not affect the *water payment*. When these pricing method are simulated in the future climate scenario, the amount of groundwater extraction is lower than that of the present in the case of the ABMs; moreover, the use of VPM results in increased extraction in the case of increasing uncertainty regarding the availability of WUA water.

	Absolute value (ha)						% variations on the baseline				
	present	Present		future			present		future		
Cultivation	VPM	ABM		VPM	ABM		ABM		VPM	ABM	
	Baseline	1	2		1	2	1	2		1	2
Forage	*8,935*	*8,935*	*8,925*	*9,050*	*9,050*	*9,016*	*0*	*-0.1*	*1.3*	*1.3*	*0.9*
Wheat	*3,679*	*3,679*	*3,679*	*3,771*	*3,771*	*3,771*	*0*	*0*	*2.5*	*2.5*	*2.5*
Barley/Oat	*850*	*850*	*850*	*869*	*869*	*888*	*0*	*0*	*2.2*	*2.2*	*4.5*
Pasture	*3,209*	*3,209*	*3,209*	*3,205*	*3,205*	*3,233*	*0*	*0*	*-0.1*	*-0.1*	*0.7*
Silage corn	*216*	*216*	*216*	*133*	*133*	*133*	*0*	*0*	*-38.6*	*-38.6*	*-38.6*
Grain corn	*867*	*867*	*867*	*660*	*660*	*660*	*0*	*0*	*-23.9*	*-23.9*	*-23.9*
Tomato	*21*	*21*	*21*	*21*	*21*	*21*	*0*	*0*	*0.0*	*0*	*0*
Artichoke	*243*	*243*	*253*	*83*	*83*	*85*	*0*	*4*	*-65.9*	*-65.9*	*-65*
Melons	*1,061*	*1,061*	*1,061*	*1,148*	*1,148*	*1,133*	*0*	*0*	*8.2*	*8.2*	*6.8*
Olive	*754*	*754*	*754*	*754*	*754*	*754*	*0*	*0*	*0.0*	*0*	*0*
Wine	*1,336*	*1,336*	*1,336*	*1,336*	*1,336*	*1,336*	*0*	*0*	*0.0*	*0*	*0*
Peach	*587*	*587*	*587*	*587*	*587*	*587*	*0*	*0*	*0.0*	*0*	*0*
	208	*208*	*211*	*190*	*190*	*191*	*0*	*1.6*	*-8.3*	*-8.3*	*-8*
Total	**21,966**	**21,966**	**21,970**	**21,807**	**21,808**	**21,807**	**0**	**0**	**-0.7**	**-0.7**	**-0.7**
Water sourcing											
Total	**16,821**	**17,007**	**17,040**	**14,841**	**15,005**	**14,939**	**1.1**	**1.3**	**-11.8**	**-10.8**	**-11.2**
WUA	13,925	14,928	14,960	11,792	12,673	12,620	7.2	7.4	-15.3	-9	-9.4
Wells	2,896	2,080	2,080	3,050	2,332	2,319	-28.2	-28.2	5.3	-19.5	-19.9

Table 8. Farming activities and water sourcing.

6. Discussion

The consequences of using different water-pricing systems for irrigation water were estimated by applying the systems under various climate scenarios (i.e., level of water accumulation in the reservoir). The first system is the one currently applied by the WUA, the Volumetric Pricing Method (VPM), based on the metered use of water by farms. The second system is an Area-Based Pricing Method (ABM), whereby fees are charged per hectare according to the estimated average water use for each crop. This system was applied in two versions: (1) employing water use coefficients that strictly reflect the actual irrigation requirements of the various crops in the area, and (2) employing the estimated average levels of water use prescribed by the WUA prior to 2001, when the switch was made to VPM. We used a DSP model to examine the application of these pricing methods in a future scenario in terms of their impacts on the use of agricultural land, on inputs (e.g., water and labour), and on the income of the agricultural sector, for the entire area and for representative farms.

The results of DSP modelling suggest that the farm sector overall is well placed to adapt to CC in the present and in the near future, particularly with respect to water accumulation in the dam. Indeed, the model predicts that increased variability in water accumulation in the reservoir would have a negligible effect on the economy of the entire agricultural sector in the study area. However, the economic impact of this increased variability shows marked differences among the farm typologies: some suffer marked reductions of income, particularly dairy farms that depend on the use of large volumes of water for the irrigation of corn.

Furthermore, the general adaptation path followed by the agricultural sector of the Nurra area is predicted to result in an increase in the environmental impact of agricultural activities, including the excessive extraction of groundwater. In this regard, the use of VPM poses problems when individual farmers have direct access to uncontrolled water sources such as groundwater, as is the case in the present study area and in many other Mediterranean areas. This problem arises because wells are generally a private asset of the farm and because there is a lack of information and legislation regarding this source of water, which would be required to control its level of exploitation. These results are consistent with the findings of other studies regarding the use of volumetric pricing (Cornish et al., 2004; Dinar et al., 1989). Furthermore, the application of ABM pricing, unlike VPM, is able to restrict the extraction of groundwater even in a scenario of increased uncertainty regarding water availability from collective, surface sources. This restriction arises because ABMs charge for the irrigation of crops regardless of the water source. Therefore, groundwater under VPM is a substitute for water distributed by the WUA, whereas under ABM it is complementary to the water distributed by the WUA, as its extraction generates extra pumping costs but does not save on other irrigation costs. This eliminates cost competition between the two water sources and results in a marked reduction in groundwater use.

These findings demonstrate that the introduction of VPMs is, in many regards, contradictory to the basic goal of environmental protection advanced by the WFD, since over-extraction could lead to increased salinization of groundwater. The pricing method can be considered a relevant strategy for adapting to the challenges of foreseen climate scenarios; hence, the adoption of a unique *a priori* strategy for water conservation may yield unsatisfactory results.

7. Conclusion

The contribution of this study is of interest primarily because it examines different pricing methods of irrigation water in a state of uncertainty, which is typical of the decision-making framework in the agricultural sector. Moreover, this condition of uncertainty is likely to become accentuated in the near future because of ongoing climate change (CC); this work sought to evaluate the impact of this change on the economics and the water management of the Nurra area . The model used for this analysis could be improved by considering the impact of additional aspects of CC (e.g., temperature, evapotranspiration and atmospheric CO_2) on crop cycles, and by considering the interactions among irrigation practices, network losses and groundwater recharging, which affect the water balance of the entire watershed.

Indeed, a reduction in the amount of water applied to crops does not necessarily correspond to increased water conservation, as farmers may respond to increased uncertainty regarding water availability by using improved irrigation technologies. These technologies generally enable reduced water application for a given level of crop consumption, or an increase in the area under irrigation for a given quantity of water applied. Neither outcome is a real saving of water; indeed, the latter would result in increased water consumption at the watershed level and less water availability downstream. However, in the present study area there exists little scope for improving the available irrigation technology; instead, farmers must consider making changes to cropping patterns.

Therefore, even considering the limitations of the model, the results indicate an advantage in adopting ABMs rather than VPM. The ABMs protect the groundwater resource and are consistent with the goal of setting prices that encourage farmers to use water efficiently, with the purpose of protecting the environmental quality of the resource.

8. Acknowledgements

Farm typologies and production technologies that characterize the agricultural sector of the area were reconstructed as part of the MONIDRI Research Project, run by INEA (National Institute for Agricultural Economics), Italy. The analysis presented in this work, however, was developed with resources of the research projects “AGROSCENARI”, funded by the Italian Ministry of Agricultural, Food and Forestry Policies (MiPAAF), and “PRIN - Il recepimento della Direttiva Quadro sulle Acque (60/2000) in agricoltura” funded by the Italian Ministry of University and Scientific Research (MIUR).

9. References

Albiac, J. & Dinar, A. (Eds.). (2009). *The management of water quality and irrigation technologies*, Earthscan London, ISBN 978-1-84407-670-3, Sterling VA, USA

Apland, J. & Hauer, G. (1993). Discrete Stochastic Programming: Concepts, Example and a Review of Empirical Application, *University of Minnesota, Department of Applied Economics, Staff Paper*, P93–P21

Bartolini, F., Bazzani, G.M., Gallerani, V., Raggi, M. & Viaggi, D. (2007). The impact of water and agriculture policy scenarios on irrigated farming systems in Italy: An analysis based on farm level multi-attribute linear programming models. *Agricultural Systems*, 93: 90-114

Bazzani, G., Di Pasquale S., Gallerani V. & Viaggi D. (2005). Water framework directive: exploring policy design issues for irrigated systems in Italy. *Water Policy,* 7:413-28

Beguería, S., López-Moreno, J.I., Lorente, A., Seeger, M. & García-Ruiz, J.M. (2003). Assessing the effects of climate oscillations and land-use changes on streamflow in the central Spanish Pyrenees. *Ambio*, 32: 283–286

Berbel, J., Calatrava, J. & Garrido, A. (2007), Water pricing and irrigation: a review of the European experience, In: *Irrigation Water pricing Policy: The Gap Between Theory and Practice,* Molle, F. & Berkoff, J. (Eds), pp. 295-327, CABI, Wallingford UK

Brooke, A., Kendrick, D.A. & Meeraus, A. (1996). *GAMS, a user guide*. GAMS Development Corporation, Washington, D.C.

Calatrava, J. & Garrido, A. (2005). Modelling water markets under uncertain water supply. *European Review of Agricultural Economics*, 32 (2): 119–142

Cocks, K.D. (1968). Discrete Stochastic Programming. Management Science. *Theory Series*, 15, 72–79

Cornish, G., Bosworth, B., Perry, C. & Burke, J. (2004). *Water charging in irrigated agriculture. An analysis of international experience,* FAO, ISBN 92-5-105211-5, Rome

Dinar, A., Knapp, K. C. & Letey, J. (1989). Irrigation water pricing policies to reduce and finance subsurface drainage disposal. *Agricultural Water Management,* 16: 155-171

Dono, G., Marongiu, S., Severini, S., Sistu, G. & Strazzera, E. (2008). Studio sulla gestione sostenibile delle risorse idriche: analisi dei modelli di consumo per usi irrigui e civili, Collana Desertificazione, ENEA, Rome

Dono, G., Giraldo, L. & Severini, S. (2010). Pricing Irrigation Water Under Alternative Charging Methods: Possible Shortcomings of a Volumetric Approach. *Agricultural Water Management*, 97 (11): 1795-1805. DOI: 10.1016/j.agwat.2010.06.013.

Dono, G. & Mazzapicchio, G. (2010). Uncertain water supply in an irrigated Mediterranean area: An analysis of the possible economic impact of climate change on the farm sector, *Agricultural Systems*, 103 (6): 361-370, doi:10.1016/j.agsy.2010.03.005

Elbakidze, L. (2006). Potential economic impacts of changes in water availability on agriculture in the Truckee and Carson River basins, *Journal of the American Water Resources Association*, 42 (4): 841-849

European Union. (2000). Council Directive of 23 October 2002. Establishing a framework for community action in the field of water policy (2000/60/EC), *Official Journal of the European Communities*, (22 December) L327

Finger, J.M. & Kreinin, M.E. (1979). A measure of export similarity and its possible uses. *The Economic Journal*, 89: 905-12

García-Ruiz, J.M., Regüés, D., Alvera, B., Lana-Renault, N., Serrano-Muela, P., Nadal-Romero, E., Navas, A., Latron, J., Martí-Bono, C. & Arnáez, J. (2008). Flood generation and sediment transport in experimental catchments affected by land use changes in the central Pyrenees. *Journal of Hydrology*, 356: 245–260

Garrido A. & Calatrava J. (2010). *Agricultural Water Pricing: EU and Mexico*, OECD, http://dx.doi.org/10.1787/787000520088

Hardaker, J.B., Huirne, R.B.M., Anderson, J.R. & Lien, G. (Eds.), (2004). *Coping with Risk in Agriculture, 2nd ed.*, CABI, ISBN 0-85199-831-3, Wallingford UK

Iglesias, E., Garrido, A. &Gomez-Ramos, A. (2007). Economic drought management index to evaluate water institutions' performance under uncertainty. *The Australian Journal of Agricultural and Resource Economics*, 51: 17–38

IPCC. (2007). *Historical Overview of Climate Change Science*, http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch1.html

Jacquet, F. & Pluvinage, J. (1997). Climatic uncertainty and farm policy: a Discrete Stochastic Programming model for cereal-livestock farms in Algeria. *Agricultural Systems*, 53: 387–407

Levine, D.M., Krehbiel, T.C. & Berenson, M.L. (2000). *Business Statistics: A First Course, 2nd ed.*, Prentice-Hall, Upper Saddle River NJ, USA

López-Moreno, J.I., Beguería, S., Vicente-Serrano, S.M. & García-Ruiz, J.M. (2007). The influence of the nao on water resources in central Iberia: precipitation, streamflow anomalies and reservoir management strategies. *Water Resources Research* 43: W09411, doi: 10.1029/2007WR005864

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J. & Zhao, Z.C. (2007). Global climate projections, In: *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of The IPCC*, Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L. (Eds), Cambridge University Press, Cambridge, New York, USA

Molle, F. & Berkoff, J. (Eds). (2007). *Irrigation Water pricing Policy: The Gap Between Theory and Practice*, CABI, Wallingford UK

Niu, X., Easterling, W., Hays, C., Jacobs, A. & Mearns, L. (2009). Reliability and input-data indiced uncertainty of EPIC model to estimate climate change impact on sorghum yields in the U.S. Great Plains. *Agriculture, Ecosystem and Environment*, 129 (1-3): 268-276

Piccolo, D. (2000). *Statistica*, Il Mulino, ISBN 8815075968

Rae, A.N. (1971a). Stochastic programming, utility, and sequential decision problems in farm management. *American Journal of Agricultural Economics*, 53: 448–460

Rae, A.N. (1971b). An empirical application and evaluation of Discrete Stochastic Programming in farm management. American Journal of Agricultural Economics, 53: 625–638

Raisanen, J. (2007). How reliable are climate models?, *Tellus Series A: Dynamic Meteorology and Oceanography*, 59: 2–29

Riesgo, L. & J. Gómez-Limón. (2006). Multi-criteria policy scenario analysis for public regulation of irrigated agriculture. *Agricultural Systems*, 91: 1-28

Semaan, J., Flichman, G., Scardigno, A. & Steduto, P. (2007). Analysis of nitrate pollution control policies in the irrigated agriculture of Apulia Region (Southern Italy): A bio-economic modelling approach. *Agricultural Systems*, 94: 357-67

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L. (Eds) (2007). *Climate Change 2007 – The Physical Science Basis*. Cambridge University Press, Cambridge NY, USA

Spiegel, M.R. (1973). *Statistica*. Collana Schaum Teoria e Problemi. ETAS Libri

Tsur, Y., Roe, T., Rachid, D. & Dinar, A. (2004). *Pricing Irrigation Water. Principles and Cases from Developing Countries*, RFF, Washington, D.C., USA

Williams, J.R., Jones, C.A., Kiniry, J.R. & Spanel, D.A. (1989). The EPIC crop growth model. *Trans ASAE,* 32:497–511

3

Irrigation Development: A Food Security and Household Income Perspective

Kenneth Nhundu and Abbyssinia Mushunje
University of Fort Hare
South Africa

1. Introduction

Rukuni, *et al,* (2006) posit that irrigation development represents the most important interface between water and land resources. Barau *et, al* (1999) stress greater emphasis on irrigation development as a means of increasing food and raw material production as well as promoting rural development. Similarly, (Hussain, *et, al,* undated) point out that agricultural water/irrigation has been regarded as a powerful factor for providing food security, protection against adverse drought conditions, increased prospects for employment and stable income, and greater opportunity for multiple cropping and crop diversification.

Furthermore, (Hussain *et., al,* undated) posit that access to reliable irrigation can enable farmers to adopt new technologies and intensify cultivation, leading to increased productivity, overall higher production, and greater returns from farming. This, in turn, opens up new employment opportunities, both on-farm and off-farm, and can improve income, livelihoods, and the quality of life in rural areas. Generally, access to good irrigation allows poor people to increase their production and income, and enhances opportunities to diversify their income base, reducing vulnerability caused by the seasonality of agricultural production as well as external shocks. Thus, access to good irrigation has the potential to contribute to poverty reduction and the movement of people from ill-being to well-being (Hussain *et, al,* undated).

Peacock (1995) defines food security as having adequate means of procuring one's basic food needs either by growing, manufacturing, mining or trading. Rukuni, *et, al* (1990) define food security as a situation where all individuals in a population can produce or procure enough food for an active and healthy life. Eicher & Staatz (1985) defined food security as a situation where all individuals in a population have access to a nutritionally adequate diet. The food security equation (Rukuni & Benstern, 1987) has two interrelated components: food availability and food accessibility. Food availability is whereby there is the availability of food through food production, storage or trade. Food accessibility is defined as the ability of the household to acquire food through production, purchases in the market from income earned or transfers.

For instance, Rukuni, *et, al* (1990) state that the largest number of food insecure households in Zimbabwe lives in natural regions IV and V, and accessing food through dry land production has been unsuccessful for most communal households given the prevailing agro-ecological factors for these regions. Populations have poor access to food because they generally lack the purchasing power that would otherwise enable them to purchase foodstuffs which they cannot cultivate. Furthermore, the incidence of food insecurity in the communal areas is largely caused by the agro ecological conditions beyond the farmers' control, high consumer prices for staple grain which erodes the household disposable income and the constraints they face in diversifying cropping patterns into higher valued cash crops.

The population densities in these natural regions IV and V have long exceeded the carrying capacity of the land, consequently leading to severe degradations of land resources in many areas, thus compromising on the efforts by smallholder farmers to break through the food insecurity trap. There are also high temperatures, lowest agricultural activities and highest incidences of agricultural failure due to frequent incidence of drought and low rainfall. The major limiting factor for the successful cultivation of crops in these regions is low rainfall and high incidence of drought. The low rainfall averages 600mm per annum, which is lower than the crop requirements for most food crops. Rukuni *et al* (1990) advocated for the need to integrate rural development interventions so as to do away with higher incidences of transitory and chronic food insecurity in smallholder communal farming areas.

Manzungu & van der Zaag (1996) postulate that one of the strategies to reduce the incidence of food insecurity in smallholder communal areas which was also advocated for by the aid organisations, policymakers, academics and lay people is a production technology appropriate for low rainfall environments. The technology is in the form of smallholder irrigation schemes. Development of smallholder irrigation schemes increases the potential for more production by counteracting mid-season dry spells and some periodic dry spells. This means that the household can grow crops more than once a year in low risk associated areas than under the rain fed production. Increased production ensures high food availability at the household level due to intensification of crop production. Intensified crop production ensures increased incomes; hence, household can purchase food, ensuring household access to food.

In this light, the Zimbabwe/European Union Micro-Project Programme (ZIM/EU MPP) has funded smallholder irrigation schemes since 1982 in Zimbabwe, but had not done any "in-depth" evaluation of the viability and impacts of these irrigation schemes, to find out whether they serve the purpose for which they were intended to and justify continued implementation of these schemes. The major objective of this study was to evaluate the impact of ZIM/EU funded irrigation projects on famers' income and food security level at Mopane Irrigation Scheme in Zvishavane District. The impact evaluation study was to justify or reform further support and investment in smallholder irrigation schemes. The study assessed the impacts on household food security and income level on a comparative analysis of irrigators and non-irrigators, and mainly looks at level of food security and incomes for both categories.

2. Literature review

2.1 Food security

Anderson (1988) points out that food insecurity may be chronic or transitory. Chronic food insecurity refers to extreme food insecurity when there is a continuously inadequate food caused by the inability to acquire food. Transitory food insecurity is whereby a household experiences a temporary decline in access to adequate food. Transitory food insecurity emanates as a result of instability in food prices, food production or people's income. In its worst form, it produces famine.

Jayne (1994) further identifies groups most vulnerable to chronic and transitory food insecurity and these include asset-poor rural people in rural and resettlement areas that farm but are often net purchasers of food. This group is said to lack the resources to produce enough income to buy their residual food requirements and this group includes female households and households in war-torn and environmentally disrupted areas, urban households with unemployed or more frequently underemployed family members. These groups typically have low levels of income and the landless labourers.

Rukuni, *et, al* (1990) argue that food security status among the households differs due to great variation in household s' resources and the ability to shift their resources into growth sectors with specific capital and climatic or infrastructure requirements. As a result, most smallholders in the semi-arid communal areas of natural region IV and V are not producing enough grain to meet the annual household demand. The existing literature suggests that the establishment of smallholder irrigation schemes has the potential of ensuring food security in the communal areas. Literature has also proposed different views regarding the possible impact of smallholder irrigation on food security in the communal lands.

Makadho (1994) states that the development of smallholder irrigation schemes dates back to 1912 and from 1912-1927 smallholders developed and managed their own irrigation schemes without government intervention. In 1928, the government took over some of the irrigation schemes when it felt that it was necessary to intervene in the development of this sector. Before independence, the majority of African smallholders in Zimbabwe were restricted to areas of poor soils and rainfall. The government therefore saw the development of irrigation schemes as a famine relief strategy.

Literature also suggests that earlier, the smallholder irrigation schemes had the assurance of food security at household level for smallholder communal farmers. The irrigation schemes did not only meet the intended objectives of increased food security, but also benefited the surrounding communities, who were not in the irrigation schemes. In concurrence, Rukuni (1984) reported that the areas that surrounded the schemes tended to provide a ready market for the food crops. The study by Rukuni (1984) showed that maize, beans, and vegetables had the greatest demand and were most prevalent on the schemes. About 70% percent of the maize sales were done locally.

A cost benefit analysis performed by Sithole (1995) indicated that irrigation increased household food security in the marginal to poor rainfall areas. The study also revealed that irrigation did not only improve the food security position of the level of the irrigators, but also the rest of the community benefited from these schemes. Sithole (1995) also revealed that the incomes of the irrigators were higher than the incomes of the non-irrigators. As a result of the higher incomes, the irrigation participants were in a position to purchase grain to satisfy household requirements to make up for any shortfall in production, as compared to non-participants. Sithole (1995) also compared the incomes and yields of the irrigators and that of the non-irrigators. Results of the study indicated that the smallholder schemes were both financially and economically viable and the participants were able to meet both the capital and running costs of smallholder irrigation schemes.

Sithole & Testerink (1983) conducted a study in Swaziland on the cropping and food insecurity aimed at evaluating how cash cropping contributed in alleviating food insecurity in Swaziland. The results indicated that it is only with irrigation that crop production can be carried out throughout the year in Swaziland. Sithole & Testerink (1983) concluded that increased crop production can be expected to encourage the establishment of more agro-industries to process the output, thereby increasing employment opportunities and purchasing power of individuals, implying capacity to purchase grain to meet the household requirements, thus increased food security.

A study by Gittinger *et al* (1990) stated that many of the world's undernourished live in large river basins in Asia, where lack of irrigation, erosion, flooding, high salinity and poor drainage represent major obstacles to improved productivity. In the semi-arid regions of Asia and Africa, the inability to harness water effectively severely limits the strength of the growing season and when the rains occur, they often take a heavy toll in flooding and soil erosion. Thus crop yields, with the existing technology of irrigation efficiency, can be doubled and increases through better control of allocation of water.

A study by Webb (1991) in a village of Chakunda in Gambia revealed that introduction of smallholder irrigation schemes increases food consumption. Webb (1991) listed the following benefits realised by participation in irrigation schemes:

- There is increased income that was translated into a boom in expenditure, investment, construction and trade.
- Backward and forward linkages resulting from traders coming to purchase irrigation produce, in this case, rice and sell cloth, jewellery and other consumables.
- Smallholder irrigation can be a worthwhile investment in the development of marginal areas of the world, coupled with the provision of irrigation facilities to communal area farmers, thus increasing yields and ensuring food security and increasing the purchasing power of the beneficiaries due to increased incomes.

2.2 Irrigation income

An income analysis for Mzinyathini scheme, carried out by Sithole (1995), revealed that the savings per hectare per month per household was Z$931.22 in drought relief. The income analysis for different groups, the project irrigators and the non-irrigators, suggested that the irrigators were in a better position to afford enough grain to satisfy household requirements than non-irrigators.

Meinzen-Dick *et al* (1993) established that among the farmers using irrigation in the natural regions IV and V, the majority (72%) were found to be food secure and had stable incomes. The study also showed that the gross margins of irrigation schemes were significantly greater than those not using irrigation. Rukuni (1985) carried out an almost similar research study in the natural regions IV and V and he showed that investment in smallholder irrigation development can have an important effect on both rural incomes and local food supplies. The results from the study revealed that the yields achieved on smallholder schemes are higher than rainfall yields in communal areas.

2.3 Viability of smallholder irrigation schemes

A report by Southern African Development Community (1992), mentioned that most recent schemes will not cover the cost of development and operation, thus are uneconomic. The SADC report noted that despite the support from the government and a donor, formal irrigation has not been formal. This is in controversy with some literature that suggests that smallholder irrigation scheme in marginal rainfall areas can only survive when supported by government.

This was supported by Mupawose (1984), when he was advocating for reduced subsidies on smallholder irrigation. The study further highlighted that irrigation schemes have failed and some are under-utilised. He further indicated that poor management had led to a decline in yield per unit area and to an overall lack of viability of the project. He cited that this was due to lack of interest and lack of farming experience by the irrigation participants.

In an economic analysis study carried out by Webb (1991) on smallholder irrigation scheme in Gambia, it was revealed that the increased income from irrigation resulted with increased expenditure, construction, investment and trade. A cost benefit analysis carried out by Paraiwa (1975), showed that irrigation schemes can play an important role in developing a cash economy for rural communities by making it possible for viable cash income to become accessible in a fairly large number of individuals.

A study by Peacock (1995) argued that smallholder irrigation development is not necessary for food security. The research was conducted based on comparing the cost of constructing irrigation in the communal areas and the cost of food relief coming into the area. It was shown that the costs of developing irrigation were higher than the cost of providing drought relief. The study also concluded that the development of smallholder irrigation for the purpose of food security was not economically viable.

2.4 Success stories of irrigation development

FAO (1997a) in a brief general overview of the smallholder irrigation sub-sector in Zimbabwe concluded that smallholder irrigation has brought success stories to farmers. The following observations were made; smallholder farmers are now able to grow high value crops both for the local and export markets, thus effectively participating in the mainstream economy, in areas of very low rainfall, as in Natural Regions IV and V, farmers enjoy the human dignity of producing their own food instead of depending on food handouts, irrigation development has made it possible for other rural infrastructure to be developed in areas which could otherwise have remained without roads, telephones, schools and clinics, smallholder irrigators have developed a commercial mentality and crop yields and farmer incomes have gone up manifold.

Similar inferences were also highlighted in a study of an irrigation scheme in the village of Chakunda in the Gambia; Webb (1991) gave the following as some of the benefits of irrigation:

- Increased income that was translated into increased expenditure, investment, construction and trade.
- Backward and forward linkages: traders were reportedly coming to purchase irrigation produce (rice) and in turn sell cloth, jewellery and other consumer items.

- Increased material wealth. At the village level, this was in the form of construction of a large mosque built through farmers' donations and an improvement of the village clinic. At household level, increased wealth could be seen in 55 houses built in the village, fourteen with corrugated metal roofing.

2.5 Challenges and constraints

Rukuni *et al* (2006) state that a number of problems have befallen irrigation schemes that are managed by central government departments, such as poor marketing arrangements, limited access to water, inability to meet operational costs due to poor fee structures and the lack of a sense of ownership, financial viability and poor governance. Some of these problems have necessitated government transferring responsibility to farmers, who have continued to mismanage these systems, hence their dilapidation. Poor maintenance and lack of effective control over irrigation practices have resulted in the collapse of many irrigation systems.

The FAO (1997) report identified a number of constraints, which hampered smallholder irrigation development in Zimbabwe. Some these include high cost of capital investment in irrigation works considering that communal farmers are resource poor, lack of reasonably priced appropriate irrigation technology for the smallholders, shortage of human resources at both technician and farmer levels, lack of decentralized irrigation service companies to give back-up service in rural areas, poor resource base of farmers, fragmented and small size of land holdings, unsecured or lack of land titles and high interest rates.

Further to the above constraints, Gyasi *et al* (2006) state that in many countries, institutional weaknesses and performance inefficiencies of public irrigation agencies have led to high costs of development and operation of irrigation schemes. Poor maintenance and lack of effective control over irrigation practices have resulted in the collapse of many irrigation systems. The study by Gyasi *et al* (2006) concluded that collective action for the maintenance of community irrigation schemes is more likely to be problematic when the user group size is large and ethnically heterogeneous, and where the scheme is shared by several communities. Use of labour intensive techniques in the rehabilitation of irrigation schemes promotes a sense of ownership and moral responsibility that help ensure sustainability. A high quality of rehabilitation works and regular training activities also contribute to successful irrigation management by communities.

3. Study area and methodology

3.1 Study area

It is estimated that at least 60% of Zimbabwe's communal farmers live in natural regions IV and V, where food insecurity is greatest (Rukuni, 2006). These areas are not suited to intensive farming systems. The research site was selected in natural region IV, an area with relatively less rainfall of less than 500mm and poor soils. This makes vast track of land unsuitable for cash cropping. The research was based on a case study of Mopane Irrigation Scheme, located in Runde area in Zvishavane, Midlands Province. The scheme has been functional since the year 2000 and the main crops cultivated are cash crops; wheat, maize, tomatoes and onions.

3.2 Sampling methods

Primary data was used as a main source of inference, while secondary data was used as a backup to the primary data. Stratified sampling was used in which the data available was divided into two strata; irrigators and non-irrigators. From each stratum, random sampling was done to obtain thirty irrigators and thirty non-irrigators. Data collection was done through structured surveys using a full administered questionnaire. The questionnaire captured data on household characteristics, asset endowment, livestock endowment, gross margin performance, agronomic practices, off-farm income, yield of grain crop. The data was entered into the Statistical Package for Social Scientists (SPSS) for further analysis.

3.3 Analytical frameworks

3.3.1 Regression analysis

A regression model was used in the regression analysis to examine the factors that affect productivity; hence food security. The project assumed the following regression model:

$$Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \alpha_4 X_4 + \alpha_5 X_5 + U_i \qquad (1)$$

Y = Food Security
$\alpha_0, \alpha_1 - \alpha_5$ are model parameters
X_1 = Asset endowment
X_2 = Household size
X_3 = Off-farm income
X_4 = Area under cultivation
X_5 = Draught power ownership
U_i = Random error term

The expected results from this regression model were as follows:

- Household asset endowment positively impacts food security.
- An increase in household size increases food security.
- Off-farm income has a positive impact on food security.
- Area under cultivation positively related.
- Draught power ownership enhances food security.

3.3.2 Gross margin analysis

Gross margin analysis was the major tool, which was used in the analysis to compare the returns between the irrigators and the non-irrigators and assess the benefits of irrigation. The study looked at the agricultural performance of both the irrigators and non-irrigators at Mopane irrigation scheme. To determine any changes in the production or productivity levels and gross incomes, a comparative analysis of inter-farm was vital. Inter-farm comparative analysis compares the irrigators and non-irrigators who are located in the same geological area.

The research study therefore used a gross margin per ha analysis as an indication of plot level performance, that is, how well farmers did on their land with the resources that were available to them. According to Johnson (1991), gross margin analysis is useful for production cycles of less than a year as this enables costs and returns to be directly linked to enterprise. Gross margin is the difference between the total sales and the variable costs.

$$\text{Gross Margin} = \text{Total Sales (Gross Income)} - \text{Variable Costs} \quad (2)$$

$$\text{Where: Gross Income} = \text{Total Volume of Output (Q)} \times \text{Price (P)} \quad (3)$$

and Variable Costs include the costs such as fertilizer, seed, crop chemicals, marketing costs, transport costs, machinery operational, labour costs, etc that would have been incurred in the production process until the produce has reached the market.

3.3.3 Farm income analysis

The crop incomes for the irrigators and the non-irrigators were derived through the use of gross margin analysis. Although the gross margin has two components that are income from sales and value of crops retained, crop output was evaluated using nominal prices. Individual household crop gross margin budgets were computed for both dry land and irrigated crops in the case of irrigators and only for dry-land for the non-irrigators. Since Mopane scheme is operated as a cooperative, only one whole farm budget was considered and then number of irrigators divided the profit to get the per income. The non-farm incomes were also compared. The main thrust behind this is to test the hypothesis that incomes of the irrigators in the project are greater than that of the non-irrigators. After computing the household gross margins, the first impressions were based on comparing the mean gross margins for the irrigators versus that of the non-irrigators.

3.3.4 Descriptive statistics

These were used to describe the differences between irrigation and non-irrigation households. Simple statistics like mean was employed to analyse data and yield, demographic characteristics, acreage and food availability. Also, socio-economic analysis like household size, ages, education, assets and other resources that can help in comparing the two sets of household were made use of.

4. Results and discussion

4.1 Demographic and endowment characteristics

It is vital to describe and compare household characteristics of sample households for primarily informing explanations for behavioural variability between irrigators and non-irrigators. Characteristics such as age, marital status, sex structure, employment, agricultural equipment endowment, livestock ownership, land ownership and ownership of other assets were considered important. This is because the asset base and household demographic structure of the household has implications on flexibility and capabilities with respect to crop production and consumption.

4.1.1 Demographic structure of households

Consideration of household demographic features offers one of the platforms on which to compare and explain behavioural variations relevant to this study.

Variable	Irrigators (Sample Mean)	Non-Irrigators (Sample Mean)
Household size	9.80	6.48
Males	3.44	2.28
Females	5.64	4.20
Household head's age	47	42
Total number of children	7.37	4.30
Children >15 years	4.99	3.02
Children <15 years	2.48	1.28
Total no. of adults	4.03	2.10

Source: Survey data

Table 1. Household Demographic Analysis

The results in Table 1 indicate that the average household size of irrigators is 9.80, higher than that of non-irrigators, with an average of 6.48 household members. There were more adults in the irrigator category with an average of 4.03 against non-irrigators' 2.10 adults. The irrigators' average household age is 47years 5years higher than that of non-irrigators (42). The irrigators have, on average more children than non-irrigators, 7.37 children per household as compared to 4.30 children for non-irrigators. This would suggest that irrigators might, on average, be more mature than the non-irrigators, who tend to be younger households on average.

Thus, the motive behind the irrigators participating in the irrigation scheme is to feed their larger household size. The larger household size may be giving the irrigators a comparative advantage, which is reflected in increasing returns to scale and decreasing average costs. For example, irrigators tend to have more labour in activities such as land preparation, where there is a great deal of labour needed, and also division of labour which increases the economies of scale.

4.1.2 Household land ownership

The quantity of land available per household is one of the most important constraints to production for communal farmers. Therefore, it is vital and valid to base comparison of irrigators and non-irrigators on the availability of arable land. This information is also important in that it will help in realising whether any disparities in household incomes may be accounted for by the rise in dry land holding.

Category	Average Size of Arable Dry Land	Average Size of Irrigable Land
Irrigators	2.26 ha	0.45 ha
Non-irrigators	2.09 ha	

Source: survey data

Table 2. Average cropping land area

The results in Table 2 show that irrigators have more dry-land (2.26ha) on average, compared to the non-irrigators who have 2.09 ha. Under this scenario, *ceteris paribus,* irrigators are expected to have more output compared to non-irrigators. The fact that irrigators have more dry land can be attributed to the fact that they might have acquired pieces of land long before the non-irrigators, who later acquired smaller pieces of land later on. In addition to dry land, irrigators have 9ha of land, which converts to about 0.45ha per household. The irrigators do work as group and the production resources are pooled together for production and the whole produce is shared and marketed as a group.

4.1.3 Livestock ownership

Livestock form an important component of household food security in the communal areas. Significant differences in livestock ownership may reasonably explain differences in food security, income and agricultural technical performance between irrigators and non-irrigators as they contribute to household food availability through production, as a production asset and through household food accessibility and through income generation.

Livestock	Irrigators		Non-Irrigators	
	Sample Mean	% Owners	Sample Mean	% Owners
Cattle	6.04	62.8	4.80	53.2
Goats	12.84	90.3	6.20	64.2
Donkeys	3.89	68.1	1.10	44.8
Sheep	0.94	42.7	0.23	21.8
Chickens	14.29	97.8	8.26	84.3
Draught animals	7.43	78.4	3.45	61.9

Source: Survey data

Table 3. Livestock ownership

The results in Table 3 show that irrigators have more livestock compared to the non-irrigators. Irrigators own an average of 6.04 cattle against 4.80 cattle for non-irrigators with percentage ownership of 62.8% and 53.2% respectively. Irrigators also have a higher number donkey per sample household of 3.89 compared to non-irrigators who have 1.10 donkeys. Better possession of draught animals would give the irrigators a comparative advantage in timeliness of tillage activities. Thus irrigators technically perform better than the non-irrigators, thus making the irrigators less vulnerable to poverty than the non-irrigators.

4.1.4 Ownership of agricultural equipment

Ownership of agricultural implements by households influences timeliness of cultivation and therefore yields. Implements can also be hired out to earn income for the households.

The results in Table 4 indicate that irrigators are better endowed with agricultural implements than non-irrigators. This implies that irrigators are wealthier than non-irrigators. However the most important tools on the farm are the plough and the hoe. Farmers often can do without such implements as scotch carts, harrows, cultivators and wheelbarrows. Since irrigators have more draught animals, it is logical and unsurprising that they also have more agricultural implements lime cultivators and scotch carts. This gives irrigators a comparative advantage in crop production in form of more timeliness in land preparation and other tillage practices. More often, the plough is used in place of a cultivator, which explains the very low number of cultivators in the two samples.

Type of implement	Irrigators		Non-irrigators	
	Sample Mean	% Owners	Sample Mean	% owners
Plough	1.46	94.7	0.96	76.3
Hoe	6.12	100	4.31	100
Wheelbarrow	2.87	78.5	1.07	66.7
Scotch cart	0.15	69.7	0.09	44.0
Harrow	0.12	23.5	0.06	16.7
Cultivator	0.23	12.6	0.11	11.2

Source: Survey data

Table 4. Agricultural equipment endowment

4.1.5 Household housing

Two types of housing structures are dealt with in this study and these are traditional and modern houses. A traditional house is taken to be a structure, which is usually round with walls, made from mud poles or farm bricks and thatched with grass, and normally one roomed. A modern house is taken to be a rectangular structure made from farm bricks or cement bricks, zinc or asbestos roofed and constitute one or more rooms.

Structure	Irrigators		Non-irrigators	
	Sample Mean	% Owners	Sample Mean	% Owners
Traditional houses	2.28	100	1.97	94..3
Modern houses	1.20	78.4	1.48	88.7

Source: Survey data

Table 5. Average number of types of housing structures of households

The results in Table 5 indicate that all irrigating households had at least one traditional house. However, non-irrigators have on average more modern houses as compared to irrigators. Also, more non-irrigators have modern houses than irrigators. The difference in modern housing may be due to the fact that since more non-irrigator household heads stay outside the village working mostly in towns or near towns, they might be bringing home the types of houses they see in towns.

4.1.6 Place of residence of household head

The place of residence of household head often indicates the opportunity cost of being in the village than anywhere else. In this case, the number of heads staying in the village may explain incentives attached to remaining in the village.

Place of residence	Irrigators %	Non-irrigators %
Village	56.7	43.3
Town	21.5	47.4
Other	12.8	9.3
Total	100	100

Source: Survey data

Table 6. Place of residence of household head

The results in Table 6 indicate that 47.4% of non-irrigators household heads stay away from the village, or employed somewhere outside the village than the non-irrigators who only constitute 21.5% who are in towns. This can be attributed to the fact that some non-irrigators get engaged in employment as mine workers at Shabanie Mine and other surrounding mines in Zvishavane. The higher opportunity cost associated with leaving the village and the irrigation scheme is higher than that of staying in the village, thus the irrigators are left with no other incentive other than that of staying in the village.

4.1.7 Household off-farm employment

Employment is defined as the number of able bodied people who are willing to work and can find a job. Table 4.7 below shows the employment status of household members.

Employment status	Irrigators	Non-Irrigators
No. employed off-farm	0.63	1.49
% with no member in regular employment (locally or elsewhere)	59.4	30
% with at least one member in regular employment	40.6	70

Source: survey data

Table 7. Employment status: irrigators and non-irrigators

Table 7 shows that on average, 1.49 of non-irrigators are employed off-farm as compared to 0.63 for irrigators. Off-farm employment generally indicate access to off-farm income particularly remittances. Again, 70% of the non-irrigators had at least one member in regular employment, as opposed to 40.6% of irrigators. This can be attributed to the fact that, as seen in the analysis above, more non-irrigators are employed in Zvishavane and other surrounding areas, while the irrigators see that it is more profitable to stay at the schemes, the reason why they constitute only 40.6% in regular employment.

5. Agricultural productivity

This subsection compares the technical performance and farm incomes to test the hypothesis that irrigators are better agriculturalists and earn more income than non-irrigators using the Gross Margin Analysis.

5.1 Land productivity

On average irrigators have more dry land an average of 2.26ha, 0.17ha higher than non-irrigators'. It is therefore expected that irrigators have more output than non-irrigators. The difference in land allocation may be explained by the efforts of irrigators seeking to meet the grain requirements of their larger households. Millet was more popular with irrigators for the purpose of beer brewing which was not so popular with non-irrigating younger women. Most land was devoted to sorghum among non-irrigators, which illustrates the lack of rainfall and risk of crop failure inherent in the Natural Region IV where Mopane scheme lies.

5.2 Dry-land production

The main source of livelihood for the farmers in Mopane area is the sale of crops. The incomes are represented in the form of gross margins, which are the incomes remaining after deducting the variable costs from the whole farm gross income.

$$\text{Gross Margin} = \text{Gross Income} - \text{Variable Costs} \tag{4}$$

Household Production Parameter	Price (US$/t)	IRRIGATORS			NON-IRRIGATORS		
		Ave Area (Ha)	Ave Yield (Ton/ha)	GI/Crop (US$/ha)	Ave Area (Ha)	Ave Yield (Ton/ha)	GI/Crop (US$/ha)
Maize (ton)	109.10	0.64	3.500	381.85	0.59	3.230	352.39
Sorghum (ton)	563.64	0.77	0.376	211.93	0.83	0.418	235.60
G/nuts (ton)	181.82	0.43	0.466	84.73	0.36	0.353	64.18
Millet (ton)	256.97	0.42	0.351	90.20	0.31	0.311	79.92
Total Av. Area (ha)		2.26			2.09		
Total GI (US$)				768.70			732.09
GI/Ha (US$)				340.13			350.28
GI/Household (US$)				11.34			10.80

Source: survey data

Table 8. Gross incomes: irrigators and non-irrigators

Maize is the most important cereal crop grown in Zimbabwe. At Mopane irrigation scheme, the crop ranks first in number of producers. As observed in the table above, there is a high yield in maize for irrigators, an average of 3.50 ton/ha, as compared to an average of 3.23 ton/ha for non-irrigators. This might be due to the fact that the irrigators, as seen in the former empirical comparative analysis, are better asset endowed than the non-irrigators, thus they perform technically better in dry land production.

However, there is a low yield of sorghum for the irrigators of 0,376 ton/ha, against 0,418 ton/ha for the non-irrigators. The irrigators grossed an average income of US$768.70 against

US$732.09 for non-irrigators from sorghum. Sorghum has better tolerance to dry conditions than maize, so non-irrigators generally devote more area to it, as a hedging strategy against food shortages.

Groundnuts yield is high within the irrigators, an average of 0,466 ton/ha compared to 0,353 ton/ha realised by the non-irrigators. This can be attributed to the fact that irrigators devote more land to its production than non-irrigators do. The difference in hectarage devoted to the crop may be explained by several factors, which include household size, total arable dry land and labour availability among others. As seen from the empirical analysis, irrigators had a comparative advantage in all of the factors above.

Irrigators have higher yields for millet of 0.351ton/ha than non-irrigators' 0.311ton/ha. It was envisaged, from informal interviews, that most irrigators are interested in income from millet through beer brewing. It was mostly older women who were interested in beer brewing, which may explain why the younger non-irrigating women were less into the crop than irrigators were. Irrigators, as seen previously, allocate more land on average for millet production than non-irrigators do. The lower yields for non-irrigators can be attributed to poor timing of cultivation activities by non-irrigators.

Crop	**Total Average Costs (US$)**	
	Irrigators	**Non-Irrigators**
Maize (US$)	109.77	75.64
Sorghum (US$)	35.39	36.61
G/nuts (US$)	17.48	11.45
Millet (US$)	19.88	30.79
Total Var. Costs (US$)	**182.82**	**154.49**

Source: Survey data

Table 9. Average total costs: dry-land production

Comparing the cost outlays for crop production between irrigators and non-irrigators, irrigators had significantly higher total variable costs of US$182.82 than non-irrigators' US$154.49, as shown in Table 9. It is believed that as a result of significantly higher use of variable inputs, compounded by more access to draught power and agricultural implements, irrigators had significantly higher output per ha than non-irrigators. This explains why irrigators seem to have a higher average gross margin than of non-irrigators as shown in the table 10 below.

Parameter	**Irrigators**	**Non-irrigators**
Gross Income (US$)	768.70	732.09
Total Variable Costs (US$)	182.82	154.49
Gross Margin (US$)	**585.88**	**29,223.36**
Average Gross Margin (US$)	**19.53**	**19.25**

Source: Survey data

Table 10. Gross margin analysis: dry-land production

5.3 Irrigation productivity

Mopane irrigation scheme produces crops during winter and summer. Total area for cropping amounts to 9ha of land. In winter, crops grown were maize, tomatoes, onions, and cabbage. Table 11 shows the hectarage allocated to each crop, average yield, price/ton, and gross income yielded, total costs in irrigation, the gross margin and the gross margin per household. Crops are grown collectively and the profits shared equally among the members.

Crop	Total Arable (ha)	Average Yield (Ton/ha)	Price of output (US$/ton)	Gross income (US$/ha)	Total Cost (US$/ha)	Gross Margin (US$)	Gross Margin/ha (US$)	Per Gross Margin (US$)
Maize	4	2.25	109.09	245.45	166.92	78.84	19.71	0.65
Tomatoes	2	4	181.82	727.27	295.10	432.17	216.08	108.04
Onion	1	0.86	96.97	83.39	16.50	66.89	66.89	66.89
Cabbage	2	2.4	121.21	290.91	78.90	212.01	106.00	56.00
Totals	**9**			**1347.03**	**557.12**	**789.91**	**408.69**	**230.98**

Source: Survey data

Table 11. Gross Income, Average Total Costs and Gross Margin for Irrigation

Overall, higher costs were incurred in the scheme's crop production than in dry-land production, which were US$182.82 in dry land against US$557.12 for irrigation. This can be attributed to the fact that irrigators have more income to meet these expenses and costs than the non-irrigators.

Maize is given the greatest hectarage in the irrigation scheme. An average yield of 2.25t/ha was obtained for maize. However, maize has a dry-land gross margin of US$381.85, higher than US$245.45 for irrigation. Other gross margins for other crops grown in the scheme were much higher than dry land gross margins for both irrigators and non-irrigators, indicating increased crop incomes for irrigators than non-irrigators. Main reasons for the higher yields of crops are: availability of water for irrigation during the dry season; access to water to counteract mid season dry spells, ability to extend the growing season, more agricultural implements and draught power; increased use of production inputs like fertilizer, economies of scale in resource use, for example, labour specialisation and access to technical advice from the Agricultural Research and Extension (AREX) personnel.

From table 8, it is observed that irrigators' average dry-land crop gross income per household is US$11.34, higher than non-irrigators' US$10.80. From the irrigation schemes, the gross income per participant is US$230.98 as shown in Table 11. In this respect, the irrigation scheme yields additional income for irrigators than what non-irrigators are getting from dry land farming.

5.4 Non-farm income

Assessing non-farm income is also important to investigate ways households supplement their income from crops. From the previous empirical analysis, it was shown that there were more non-irrigators than irrigators who stayed away from the village, employed somewhere outside the village and in Zvishavane. Though irrigators have, in terms of crop incomes outperformed non-irrigators, they might be more successful in other areas like off-farm work. As a result, there is need to evaluate and compare non-farm income of the two categories. An attempt was made to cover a number of income-earning activities in the area.

Source of Income	Irrigators		Non-irrigators	
	Mean (US$)	**% of Total Income**	**Mean (US$)**	**% of Total Income**
Remittances	21.88	10.0%	55.15	28.5%
Hiring out family labour	29.82	14.7%	26.73	13.8%
Hiring out agric implements	24.85	11.4%	5.33	2.8%
Sale of livestock	22.30	10.2%	14.55	7.5%
Building activities	32.12	14.7%	46.73	24.1%
Beer brewery	16.36	7.5%	12.42	6.4%
Cross Boarder	30.30	13.9%	17.58	9.1%
Shop business	40.48	18.6%	15.09	7.8%
Totals	**218.12**	**100%**	**193.58**	**100%**

Source: survey data

Table 12. Other sources of household income

Table 12 above examines the other sources of income besides cropping. Remittances were vital in non-irrigators with 28.5% contribution to total income, compared to 10.0% for irrigators. This is because more members from non-irrigating households are in regular employment as previously shown in Table 7. The highest income earner to irrigators is shop business, representing a contribution of 18.6% compared to 7.8% for non-irrigators. However, building activities tend to contribute significantly to both irrigators and non irrigators, with a contribution of 14.7% and 24.1% respectively.

Irrigators have more income on average, (US$218.12) against US$193.58 for non-irrigators. This can be attributed to the fact that irrigators have more livestock, which they sell as reflected by a proportion of 10.2% for irrigators compared to 7.5% for non-irrigators, and more agricultural implements, which they hire out. The larger size of the irrigators also gives them the opportunity of hiring out family labour which also contributes to the average income for irrigators as compared to non-irrigators.

Some females, from both categories are also involved in trading activities where they go to countries like South Africa where they buy other goods for resale. This contributes significantly to both the incomes of both, though female irrigators gross more from such activities. It is also important to say that since irrigating households are bigger and older they have greater division of labour and diversified off-farm income sources. This confirms that income of irrigators is greater than that of non-irrigators since the irrigators have more income in dry land and irrigation activities as compared to the non-irrigators.

5.6 Regression analysis results

Applying the regression model, the econometric results are presented as in Table 13 below. The dependent variable is food security. The estimates indicate essentially in accordance with the hypothesis that the irrigators are more food secure as compared to the non-irrigators. The variables in the model that affect household food security include household size, sex of household head, off-farm income, area under cultivation and draught power ownership. Each parameter estimate measures the relationship or contribution of each variable to the food security level per household.

Independent Variable	Parameter Estimate	T- value	Significance
Intercept (constant)	- 45.326	- 0.429	0.528
Household size	88.423	2.914	0.107*
Household asset endowment	- 31.853	- 1.495	0.163
Off-farm income	5.265	2.480	0.14*
Area under cultivation	0.839	3.486	0.0485*
Draught power ownership	9.202	2.146	0.058**
Random error term	86.574		

Source: survey data

Table 13. Regression analysis model and the estimates

$R^2 = 0.718$ Adjusted $R^2 = 0.641$

* - indicate significance at the 5% level
** - indicate significance at the 5% and 10% level

The results indicate R^2 is 0.718, implying a degree of 71.8% relationship among the independent variable. The adjusted R^2 shows that 64.1% of the variables can explain the model and the higher the adjusted R^2, the more significant the model. Therefore, the variables can significantly explain the model.

Household size, as can be seen Table 13 is significant at the 5% level and the positive coefficient indicates that there is a positive relationship between food security and household size. It was observed in the previous analysis that irrigators were seen to have a higher household size on average than the non-irrigators. This explains why food security increases with an increase in household size since more labour will be available to work in the irrigation and dry land plots, including hiring out labour and raise income to purchase more food. This supports the hypothesis that irrigators are more food secure and higher incomes compared to non-irrigators.

Off-farm income is also significant at the 5% significant level and the coefficient is positive. This indicates that an increase in off-farm income leads to an increase in the food security. As previously observed in the preliminary analysis of the study, the irrigators had more off-farm income than non-irrigators, thus it can be concluded that they are more food secure than the non-irrigators. This again supports the hypothesis that irrigators are more food secure than non-irrigators.

The area under cultivation is also seen to positively affect household food security. This is shown by a positive coefficient in the model. This means that as area under irrigation increases, household food security also increases. It is also, at the 5% significance level true that irrigators are more food secure compared to non-irrigators. This is because the irrigators were seen to own, on average more land than non-irrigators did, coupled with that from irrigation. This can be attributed to the fact that they can produce more per given area, thus boosting their food production for the family.

Draught power is also another variable that is seen to positively affect the level of household food security. This is significant at the 5% level and can safely support the hypothesis that irrigators are more food secure since they were seen to have more draught power on average than non-irrigators. As a result, they engage in timeliness ploughing, thus aiding in boosting output production.

6. Conclusions

6.1 Socio-economic characteristics of the household

Irrigators were found to be larger households and older than non-irrigating households. Non-irrigators had more members in regular employment than irrigators, suggesting more income to non-irrigators from remittances. Irrigators have more livestock on average than non-irrigators. On agricultural equipment, irrigators were better endowed than non-irrigators were. On housing, non-irrigators' houses were more modern as compared to those of irrigators. Finally, irrigators had more land than non-irrigators suggesting increased production of more food from dry land cropping than non-irrigators. Non-irrigators seem to be more into off-farm regular employment than irrigators.

6.2 Impact on food security

The study has presented some evidence to show that irrigators produce more food than non-irrigators. The output of irrigators from dry-land and irrigation is greater than non-irrigators' output from dry land production. The irrigators were also seen to have more dry-land on average, coupled with that from irrigation as compared to non-irrigators. As a result, they had more crop output compared to the non-irrigators. This ensures availability of food for them. From the gross margin analysis, it was seen that irrigators had more crop income, and coupled with non-farm income, they have more disposable income, which they can use for purchasing household food requirements which cannot be locally produced.

The irrigation scheme has also been seen as a source of food where non-irrigators would buy the produce like cabbage, tomatoes and onions. Thus, irrigators have more disposable income as compared to non-irrigators. More income implies a much better security position for irrigators giving them the opportunity to purchase more nutritious foods. As was observed, the farmers grow cabbages, onions and tomatoes and these crops do help in relieving malnutrition. Thus, the hypothesis that irrigation increases the food security level in the communal areas is therefore accepted, provided that food markets are available.

6.3 Impact on farm incomes

It has been shown from the study that irrigation increases the incomes of the smallholder irrigation farmers through crop incomes. This was done on a comparative analysis scenario where the gross margins from dry land for both the irrigators and non-irrigators were computed. The larger contribution of income from irrigation has evidenced that the irrigation scheme increased the incomes of irrigators substantially, and was largely responsible for the significant difference in the income levels between both categories. Higher incomes improve the standard of living; hence irrigation improved the welfare of irrigators.

The evidence supports the hypothesis that irrigators have more income as compared to non-irrigators. An analysis of other sources of income was conducted and showed a higher off-farm income for irrigators than of the non-irrigators'.

6.4 Technical performance

Smallholder irrigation schemes increase agricultural productivity. Irrigators were seen to perform better than non-irrigators. This is attributed to the fact that irrigators are better factor endowed, had more draught power and labour force. This means they practiced timeliness agricultural activities, thus increasing agricultural productivity. Irrigators also have better access to extension services through AREX personnel who constantly disseminate information to them, unlike non-irrigators who often meet him after a long period. Thus, we fail to reject the hypothesis that irrigators are better agricultural performers than non-irrigators.

7. Policy insights

Irrigation, as has been established from this study, positively impacts on the irrigators through improving household food security and income, hence standard of living for the irrigators. As a result, ZIM/EU MPP, together with the government and private sectors, should be encouraged to invest more in smallholder agriculture. Increases in the incomes realised from irrigation scheme contributes to the Gross Domestic Product, which is an aspect of economic growth. Hence, irrigation contributes to economic growth of the nation.

The irrigation scheme was seen to make a positive contribution to household food security, thus, it is a way of ensuring that people have access to adequate, nutritious food in their homes. This improves on the standards of living of the rural poor.

8. Recommendations

The study shows that smallholder irrigation can make a significant contribution towards poverty alleviation, increased incomes and food security. As such, ZIM/EU MPP and other donor NGOs should continue and be encouraged to support smallholder irrigation scheme investments. This should spread to all areas in the country, especially to those communal areas where rainfall is erratic. This will ensure food security, increased incomes, improved standards of living and employment creation for the rural population.

Governments, public and private institutions and non-governmental organisations are recommended to work together defining and implementing comprehensive strategies for smallholder irrigation development especially in the smallholder communal areas so as to ensure food security and employment to the rural population. There is need to formulate a comprehensive strategy to promote small-scale irrigation, including the accessibility of appropriate and affordable technology.

Such a strategy should include the following components:

- Review existing regulations and policies that influence small-scale irrigation.
- Define the role of government institutions, private sector and non-governmental organizations (NGOs) in promoting the adoption of improved irrigation technologies by small farmers. The private sector and NGOs should be encouraged to participate. However, it is recognized that government should play an active part in the identification and development of appropriate technologies and in the wider issues of rural infrastructural development so as to encourage expansion of smallholder irrigation projects.
- Encourage private investment in irrigation through provision of credit and financial incentives targeted to smallholder irrigation.
- The local rural district councils should make sure that they get in touch with NGOs, like ZIM/EU MPP and the donor community willing to take part in establishment and development of smallholder irrigation schemes, leading to self-sufficiency and food security.

9. References

Anderson P. P. (1988). Food Security and Structural Adjustments. World Bank, Washington, D.C.

Barau, A.D., T.K. Atala And C.I. Agbo (1999). Factors affecting efficiency of resource use under large scale farming: A case study of dadin kowa irrigation project, Bauchi State. Nig. J. Rur. Econ. Soc., 1: 1-6.

Eicher C. & Staatz J. (1985). Food Security Policy in Sub-Saharan Africa. Invited Paper Prepared For The XIXth Conference Of The International Association Of Agricultural Economists, August 25 – September 5 1985. Malanga, Spain.

Gittinger, J., Chernick, S., Hosenstein, N.R. and Saiter, K., 1990. Household food security and the role of women. In: *World Bank Discussion Paper No. 96*, the World Bank, Washington, DC.

Hussain I, Mark Giordano M, & Munir A (Undated). Agricultural Water and Poverty Linkages: Case Studies on Large and Small Systems. http://www.iwmi.cgiar.org/propoor/files/ADBProject/ResearchPapers/Agricultural water poverty_linkages.pdf. Accessed 01 August 2010.

Jayne T. S. (1994). Market-oriented Strategies to Improve Household to Food Experience from Sub-Saharan Africa. MSU, International Development Working Paper No. 15, Department of Agricultural Economics, Michigan State University.

Johnson D. T. (1991). The Business of Farming. A Guide to Farm Business Management in the Tropics. McMillan Publishers Ltd, London.

Makadho J.M. 1994. An Analysis of Water Management Performance in Small holder Irrigation Schemes in Zimbabwe. A dissertation submitted to the Department of Soil Science and Agricultural Engineering in partial fulfillment of the requirements for the degree of Doctor of Philosophy. University of Zimbabwe.

Manzungu E & van der Zaag P (1996). The Practice of Smallholder Irrigation. Case Studies from Zimbabwe. University Of Zimbabwe Publication Office, Harare.

Meinzen-Dick R, Makombe G & Sullins M. (1993). Agro-economic Performance of Smallholder Irrigation in Zimbabwe. Paper Prepared For UZ/Agritex/IFPRI Conference On Irrigation Performance In Zimbabwe, 1-6 August 1993 At Montclair Hotel, Juliasdale.

Mupawose R.W. (1984). Irrigation in Zimbabwe. A broad overview in Africa Regioal Symposia on Smallholder Irrigation. Edited by Blackie, 1987, University of Zimbabwe, Harare.

Paraiwa, M.G. (1975). *An economic analysis and appraisal of Chilonga rrigation scheme in Matibi Tribal Trust Land*. Economics and Marketing Branch, Ministry of Agriculture. Zimbabwe

Peacock T. (1995). Financial & Economic Aspects of Smallholder Irrigation in Zimbabwe & Prospects for Future Development in Water Development for Diversification within Smallholder Farming Sector. Paper presented at Monomotapa Hotel, Harare, May 30 1995. Zimbabwe Farmers Union.

Rukuni M & Benstern R. H. (1987). Major Issues in Designing a Research Programme on Household Food Insecurity in Southern Africa. Food Security Policy Option. UZ/MSU.

Rukuni M & Eicher C. K. (1987). Food Security for Africa. University Of Zimbabwe, UZ/MSU. Food Security Project. University of Zimbabwe Publications, Harare.

Rukuni M, Eicher C.K & Blackie (Eds). (2006). *Zimbabwe's Agricultural Revolution, Revisited*, University of Zimbabwe Publications, Harare.

Rukuni, M. 1984. Cropping patterns and productivity on smallholder irrigation schemes. In: Blackie, M.J. (editor) *African regional symposium on smallholder irrigation.* University of Zimbabwe.

Rukuni, M., Mudimu, G. and Jayne, T. (eds.) 1990. *Food Security Policies in the SADCC Region*. Proceedings of the 5th Annual Conference on Food Security Research in Southern Africa, 16-18 October, University of Zimbabwe, Harare.

SADC (1992). Regional Irrigation Development Strategy. Country Report, Zimbabwe. ACK Australia Pvt Ltd, Harare.

Sithole P.N (1995). The Impact of Smallholder Irrigation on Household Food Security in Marginal Areas.

Sithole, V.M. and J. Testerink. (1983). "Irrigation and food security in Swaziland: current status and research priorities". Paper presented at the 4th Annual University of Zimbabwe/Michigan State University Conference on Food Security in Southern Africa, 31 October – 4 November, 1983. Social Science Research Unit, University of Swaziland, Swaziland.

Webb (1991). When Projects Collapse; Irrigation Failure in Gambia From a household Perspective. Reprinted From Journal Of International Development. Volume 3. No 4 July, Washington DC, USA.

www.cso.co.zw, Real Values, Nominal Values and the Price Index, Accessed 18 September 2008.

Webb P (1991). *When projects collapse: Irrigation failure in the Gambia from a household perspective.* Journal of International development Vol. 3, No. 4. July Institute, Washington D.C.

GYASI, ENGEL & FROHBERG (2006). *What determines the success of community-based institutions for irrigation management?* ZEF Policy Brief No. 5, Ghana

4

Water Rights Allocation, Management and Trading in an Irrigation District - A Case Study of Northwestern China

Hang Zheng[1], Zhongjing Wang[1], Roger Calow[2] and Yongping Wei[3]
[1]State Key Laboratory of Hydro-Science and Engineering, Department of Hydraulic and Hydropower Engineering Tsinghua University, Beijing
[2]Overseas Development Institute, London
[3]Australia-China Water Resource Research Center, Department of Civil and Environmental Engineering, University of Melbourne, Melbourne, Victoria
[1]China
[2]UK
[3]Australia

1. Introduction

Demographic change, growing urbanization, intensification of agriculture and climate change all pose a continual challenge to the availability of water resources. The increasing competition for water demand among the sectors of human activities and for the environment requires the development of policies for water resources sustainability.

Policies to expand water resource supplies are currently not in vogue because they involve the regulation of water through physical impediments such as the construction of dams, weirs and channels. Over the last few decades demand management policies involving water pricing, assigning water rights and introducing water markets have received increased emphasis. Water rights, a prerequisite for water markets, are considered as a key water management instrument to improve water use efficiency.

In response to concerns of increasing water scarcity and seriously degraded river ecosystems, water policy in China over recent decades has shifted from investing in large storage and delivery infrastructure to policies and institutions designed to allocate the existing resource more efficiently. The definition and establishment of water rights allocation systems are important components of water management reform. Water rights allocation systems did not exist in China before 1988. The 1988 Water Law and its revision, the 2002 Water Law, have introduced initial water rights allocation across the country. In China, water rights are defined by the state according to the priorities assigned to competing users. Water resources in a trans-provincial (or prefectural) basin are shared amongst the jurisdictions administratively.

Northwestern China faces more severe water shortages for its arid climate. The agriculture water use is above 80% of total water use in this region. Therefore, agriculture water rights reform raises much concern currently. In some areas, the water rights defined for province or prefecture are allocated further to the irrigation districts and farmers. Then, the water trading happens in these places. For example, Hangjin Irrigation District on the south bank of the Yellow River, Inner Mongolia has traded some of its irrigation water to downstream factories. The trading is termed "irrigation water-saving supported by industrial investment, with saved water traded to industry". At the same time, Hangjin Irrigation District has conducted a comprehensive reform of irrigation water management focused on water rights.

This proposed chapter aims at introducing a framework for water rights allocation, management and trading in the farmers' lever, in order to address: (1) how the long-term water rights can be defined for the individual farmers in order to share the total water resource of the irrigation district; (2) how the farmers' water rights are administrated, monitored and accounted; (3) how the farmers to trade their water rights with the industry users or other farmers in the context of current Chinese Water Law.

The chapter will describe the current status of water management in the Hangjin district, outlines some of the problems water trading has produced, and presents a framework for further water rights reform focused on rights allocation, the granting of volumetrically-capped water certificates and tickets, water use planning and monitoring, and the responsibilities of water user associations in ensuring that individual farmers receive fair allocations. In additional, a water trading approach based on "water extraction period exchange" in Taolai irrigation distract, Gansu, China will be discussed in the chapter. The chapter then summarizes key recommendations of relevance to Hangjin and Taolai and other irrigation districts in China.

2. Water rights allocation among the farmers

2.1 Introduction

The Inner Mongolia Autonomous Region in China enjoys exceptional advantages. In particular, the region has an abundance of natural resources for the development of mining, electric power, metallurgy, chemical, and machinery processing industries. The Region plans to use these resources to build a large energy base in the "golden triangle" of Hohhot, Baotou and Ordos (Figure 2.1) to create an affluent society. However, the serious shortage of water resources hinders the development of the regional energy industry, and the region's allocation of water from the Yellow River Conservancy Commission (YRCC) is already fully committed. It is under such circumstances that that the autonomous region initiated a pilot program involving the transfer of water rights. Since 2003, a number of pilot projects for water right transfer have been launched by the YRCC and the Inner Mongolia Department of Water Resources (Shen et al. 2006), aimed at meeting the growing water needs of downstream industrial users.

One of the first such pilots has involved Hangjin Irrigation District. Beginning in 2004, the newly established Office of Water Rights and Transfer in Ordos city has overseen a program in which water saved through canal lining in the district is transferred to downstream industries, with the costs of lining met directly by the industrial beneficiaries. According to the Inner Mongolia Autonomous Region Water Rights Transfer Planning Report, in the three-year period from 2005 to 2007, 13 enterprises invested a total of RMB 600 million in canal lining. According to the plan, the implementation of the project will save as much as 138 million m3 of water. Industrial users funding the capital costs of canal lining are also obliged to meet the ongoing operations and maintenance costs of canal repair over a 25 year term.

The channel lining and water transfer program in Hangjin highlights one response to a wider problem in China – the problem of increasing scarcity and growing competition for water between uses and users. In this context, agriculture is under growing pressure to release water to urban and industrial users. Clear rules are needed for doing this and, increasingly, clear rights will be needed within irrigation districts (IDs) so that farmers can be confident about how much water they will get, and when they will get it. Moreover, a system of clearly defined, secure water rights provides the foundation for many other reforms aimed at managing demand and increasing efficiency, including water pricing and water trading.

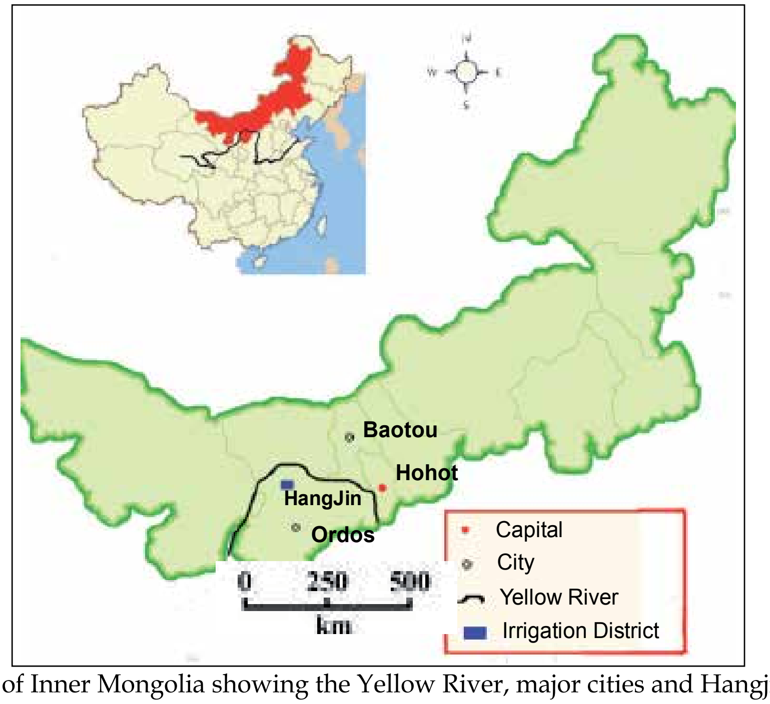


Fig. 2.1 Map of Inner Mongolia showing the Yellow River, major cities and Hangjin ID

2.2 Hangjin irrigation district

Hangjin County is located to the northwest of Ordos City in Inner Mongolia (Figure 2.1). Along its northern margin the Yellow River winds down with a length of roughly 253 km, making Hangjin County the longest flowing section of Yellow River of all counties nationwide. The county includes nearly 40,000 ha of designated farmland along the Yellow River, and is one of three major irrigation zones of Inner Mongolia. It is also one of China's main grain producing areas. Hangjin Gravity Irrigation District (HID) in Hangjin County – the focus of this study – is the only irrigation district in Ordos with the right to take water from the Yellow River. HID is located on the south bank of the Yellow River and covers an area of approximately 23,000 ha. Of this, roughly 21,000 ha is gravity fed and 1700 ha is pumped (at the head of the system).

Hangjin Irrigation District draws all of its water from the Yellow River. Its water use is therefore controlled, ultimately, by the YRCC, which sets minimum flow requirements for the river at provincial/regional boundaries based on an Annual Allocation Plan (Table 2.1), and allocates relative shares to individual provinces and regions according to supply and demand conditions. In a normal year, Inner Mongolia therefore receives 5.86 billion m^3 out of a total flow of 37 billion m^3. The maximum (sometimes termed 'normal') gross diversion to the Hangjin district –the permitted volume – is 410 million m^3 per year, including a mandatory return flow of 35 million m^3 per year. So, the normal net diversion to HID is 375 million m^3. Return flows are fed back to the river through four main drainage channels. Savings of 130 million m^3 per year from canal lining, traded out of the irrigation district, will leave an ongoing diversion of 280 million m^3 per year, illustrated in Figure 2.2.

Province/ region	Qinghai	Sichuan	Gansu	Ningxia	Inner Mongolia	Shaanxi	Shanxi	Henan	Shandong	Heibei & Tianjin	Total
Annual water use billion m^3	1.41	0.04	3.04	4	5.86	3.8	4.31	5.54	7	2	37
%	3.8	0.1	8.2	10.8	15.8	10.3	11.6	15.0	18.9	5.4	100

Table 2.1 Water allocation in the Yellow River (YRCC, 2005)

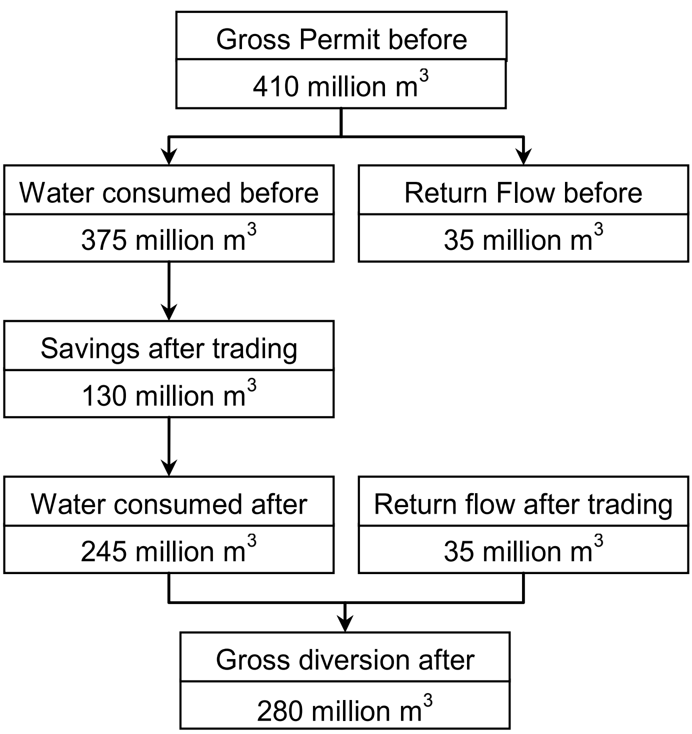


Fig. 2.2 Diversion, consumption and return flows for Hangjin Irrigation District

By 30 September 2006, a total of six canal lining subprojects had been completed, each funded by a separate industrial enterprise. The idea of "Industrial Investment in Water Saving for the Transfer of Agricultural Water Rights" has helped alleviate the water shortages experienced by industry, and has also helped reduce the burden of farmers by saving water and reducing farm costs. Currently, the annual water fee for each householder has been reduced by around 20-30 RMB/year. Farmers' costs have reduced because they no longer have to pay for water losses in the channels that deliver water to the point where water user associations (WUAs) make bulk purchases on behalf of the farmers they represent.

The channel lining and transfer project has had many benefits. However, trading has also created a number of problems, particularly for the irrigation agency that is responsible for managing and maintaining irrigation infrastructure above WUA purchase points – Hangjin Irrigation Management Bureau (HIMB). Moreover, the rights of farmers within the district remain ambiguous.

A framework for a modern system of volumetrically defined water rights in HID has been developed (WET, 2007). It is proposed that this serves as a template for guiding reform in other IDs in China as competition for water increases, and agricultural users face growing pressure to account for their water and release 'surpluses' to urban and industrial users.

The sections below discuss rights definition, allocation and management issues within HID. The principal focus is on improving the distribution of water within an ID so that farmers receive secure, transparent and equitable allocations within the overall permitted allowance of the ID.

2.3 Long-term Initial water rights allocation

Drawing on field work conducted in HID, WET (2007) describes how the water diverted to the district under its irrigation permit is currently allocated through main and branch canals, and down to individual farm households. In common with many IDs in water-scare northern China, the allocation process combines bulk volumetric charging to farmer groups (increasingly WUAs) established on branch canals, with area-based charging for farmers. Water User Associations purchase pre-paid water tickets on behalf of farmers, and are responsible for (amongst other things) distributing water within their command areas and collecting fees.

WET describe how water allocation to WUAs could be improved according to the principles of fairness, efficiency and environmental sustainability, amplified below. They also describe how the water rights of WUAs could be volumetrically defined and capped through the issue of Group Water Entitlements (GWEs) at the point at which WUAs pay for bulk deliveries. Below this point, farmers would continue to pay for water on an area basis, as delivery and monitoring infrastructure in Hangjin, and most IDs in China, is not in place to monitor individual entitlements at the household level.

A volumetric cap on the water rights of WUAs needs to fully consider existing patterns of water use within and between WUAs, and the experience of farmers, WUA representatives and HIMB staff in administering present systems. Hence it is proposed that rights allocation follows existing practice by linking land and water rights. In other words, rights assigned would be directly linked to the (existing) irrigated areas of each WUA, and could not be negotiated upwards by a WUA seeking to expand its irrigated area or plant more water-intensive crops, for example. Hence one objective of defining and enforcing WUA-based GWEs would be to end the requirements approach to water use planning that currently prevails so that, in future, water savings rather than additional supply would be used to maintain or increase farm production and farmer incomes.

Different regions and different groups of people should enjoy equal rights to water for survival and development. Hence the allocation of rights should guarantee fairness between different management sections of an ID, different WUAs and different water users and, in particular, afford protection to those farmers with small land holdings. In defining and allocating rights, consideration should also be given to 'third party' impacts on (linked) environmental services and other downstream users, such as groundwater users dependent on return flows from the irrigation district. How can the GWEs of individual WUAs be calculated to account for these factors, and to account for channel losses incurred to the points in the system at which WUAs purchase water? WET (2007) describe the calculations involved. A water allocation model is used in the water rights allocation process. The farmers' irrigation land area and crop mix are considered in the model (Figure 2.3).

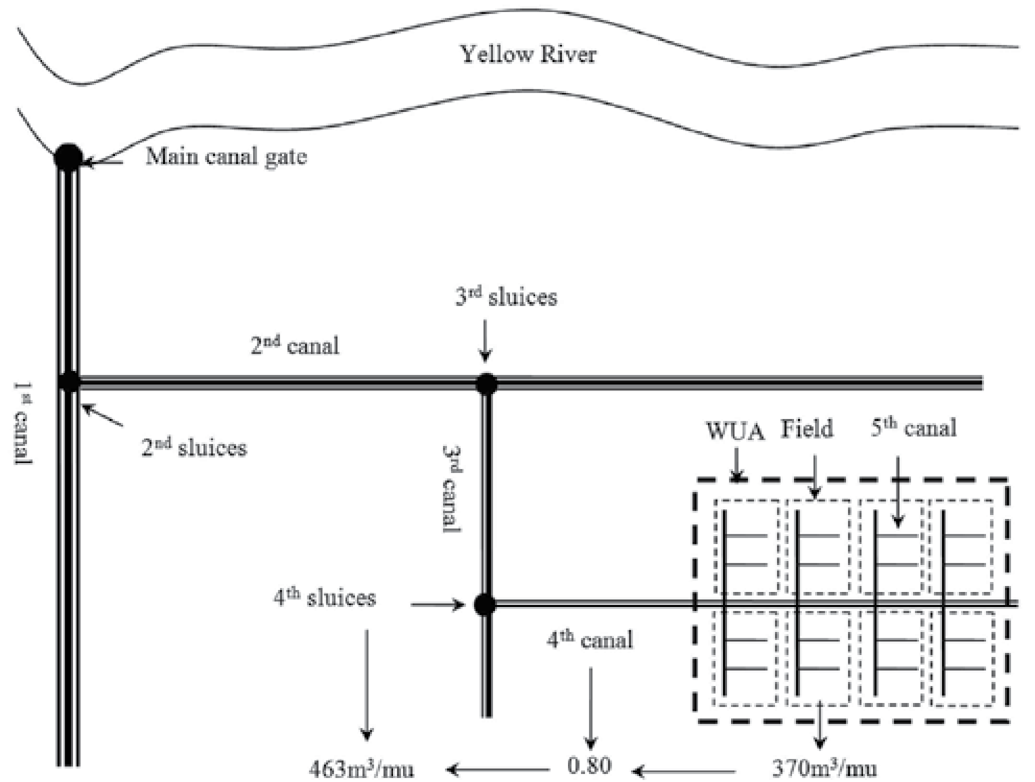


Fig. 2.3 Water allocation model for HID

The combined irrigated area of all 43 WUAs in the gravity flow section of HID is estimated at 21,322 ha. The total volume of water that needs to be delivered to fourth level sluices (and therefore WUAs), after subtracting losses in the canals above, is estimated at

143 million m^3/year. The total volume of water that needs to be diverted from the Yellow River to meet WUA requirements and cover conveyance losses is 225 million m^3/year. Total losses in the canals above fourth level sluices are estimated at 82 million m^3/year. Using this data, and similar calculations covering allocations to individual WUAs, the long term, initial water rights of each WUA in HID can be determined as GWEs. These, in turn, form the basis for the issue of water certificates.

In contrast to the current farmer-driven approach to estimating water needs in ID, such an allocation provides a more scientifically-sound basis for defining and capping rights within the overall allowance of the irrigation district, and for accounting for all transmission losses through main and branch canals to WUAs. Since losses in each canal have now been estimated, future conservation efforts – including trading in transmission savings – can be better targeted and quantified. In this way, the approach to defining and allocating GWEs described above can form the basis for rights reform in other IDs.

3. Water rights management in an irrigation district

An integrated framework of irrigation water use in compliance with the farmers' water rights will be proposed in this section for Hangjin irrigation district, including the water use monitoring and accounting, accounting the farmers' water use to ensure that their water uses are under the allocation quota and water tickets as well as the role of water users association, et al.

3.1 Water rights certificates and water tickets

A system of water rights certificates can be used to formalise the rights of WUAs, providing information on long-term rights (defined by GWEs), annual water entitlements (defined by available supply in any given year) and the water purchased in each irrigation period. In addition, the system can provide information on any water transactions that have occurred between WUAs, and between WUAs and the irrigation management agency. Table 3.1 provides a summary of certificate functions and uses.

Function	Use
Voucher for long term rights	The irrigation management agency records each WUAs long-term water rights (GWEs) in a water certificate.
Calculation of purchase limits	At the beginning of the year, the irrigation management agency calculates the water purchase limit (annual entitlement) of each WUA and records this information on the certificate. After purchasing tickets in each irrigation period, the purchase amount will be recorded on the certificate to calculate the remaining purchase limit for the following periods. WUAs can purchase tickets up to the limit.
Record of water trading	The irrigation management agency records all information on water transactions.
Reference for water rights reallocation	The irrigation management agency will accumulate data on actual water use across seasons and between years, helping to guide any future adjustment.

Table 3.1 Functions and uses of water certificates

To establish and operate such a system, the following steps are proposed (WET, 2007):

- After an initial water rights allocation process, the irrigation agency grants rights to each WUA in the form of a water certificate. This will show each WUAs long term water right.
- At the beginning of each year, the agency calculates the proportional water share that each WUA is entitled to (an annual entitlement) based on expected water availability in that year.
- Before each irrigation, the agency adjusts, as necessary, each WUAs annual entitlement in light of predicted supply to give a corresponding water purchase limit for all remaining irrigation periods. The purchase limit is recorded on each WUAs water certificate.
- After purchasing water tickets in any given irrigation period, the purchase amount is recorded on the certificate to calculate the remaining purchase allowance, or entitlement, of the WUA for the next period. In other words, a process of continuous water accounting is adopted between irrigation periods.
- Any water trading is recorded by the relevant agency section office on the water certificates of both buyer and seller. Trading with other sections is also checked and registered with the agency. Certificates would also show actual water deliveries after trading.

After a reasonable period of operation (5-10 years), the irrigation management agency can review certificates in light of actual water use and trading experience, and revise as necessary. Following any long term trade of water rights, the irrigation management agency can take back old certificates and issue new ones after thorough auditing and recording.

For each WUAs purchase of water, it is proposed that the current system of pre-payment through water tickets is continued. Water tickets provide the basis for water purchase, water delivery and water trading within prescribed limits. The ticketing system can ensure that both WUAs and the irrigation management agency have clear information on prices, deliveries and volumetric rights, allowing WUAs to trade savings freely (Wu & Wu, 1993). Water User Associations would buy water tickets according to their water certificates before each irrigation, and would also be allowed to purchase extra water from those WUAs deciding not to use their full allowance (Feng & Li, 1993). Table 3.2 provides a summary of ticket functions and uses.

Function	Use
Support for permit control and quota management	WUAs buy tickets up to their caps; HIMB sells tickets according to water availability and water rights limits.
Pre-payment for water	Water is only supplied by HIMB once WUAs have purchased tickets.
Water trading and monitoring	WUAs can buy and sell 'saved' tickets; HIMB monitors ticket turnover and adjusts caps as necessary.
Payment voucher – rights and duties	Tickets provide information on GWEs, actual delivery and payment – a summary of entitlement and payment obligation.

Table 3.2 Functions and uses of water tickets

In summary, water rights certificates would formalise the long-term water rights of WUAs within an ID. Water tickets would then 'translate' these rights into real-time rights for WUAs, allowing them to purchase water within the cap for a specific period, and according to how much water has been purchased previously. Long-term and real-time water rights are then connected through water use planning, which converts long-term GWE into the real-time water cap and water use scheduling according to the planned water demand and the runoff forecast of the river. The relationship between water rights, water rights certificates and water tickets is shown in Figure 3.1.

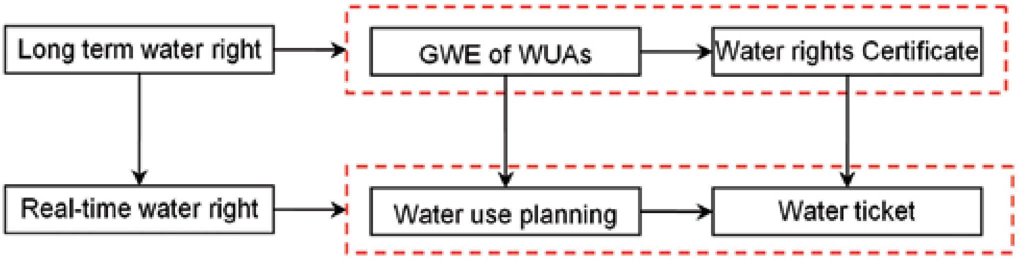


Fig. 3.1 Relationship between water rights certificates and water tickets

3.2 Water use planning

The objective of water use planning is to schedule water diversion, storage, delivery and use in an ID according to the requirements of farmers, available supply from the river and flow through the irrigation channel system. A water use plan is a guideline for the rational delivery and use of water within an ID, and can help improve irrigation efficiency and save water. In this section, it is proposed that the water use plan takes the GWEs discussed previously as a starting point, and then translates them into a real-time irrigation schedule for WUAs. WET (2007) propose that this occurs through a computer-based model that can balance demand and supply, guide allocation between WUAs and help manage rights in a quick and transparent manner.

At the beginning of the year, the annual water use plan for the ID would be prepared by the irrigation management agency, based on the annual water use plans submitted by each WUA (within capped limits), and submitted upwards through the irrigation agency to the higher level department for approval, such as the river basin management department. The river basin management department would then revise and approve the annual available water cap and the water scheduling of the ID, according to the water abstraction permit of the ID and the annual runoff forecast of the river. Afterwards, the irrigation district management agency would adjust the annual plan accordingly, and announce it to WUAs.

Prior to each irrigation, a WUA would then prepare and submit a plan for that period to the irrigation management agency for approval. The agency would check the available water allowance for each WUA, accounting for previous purchases, use under cap and overall irrigation scheduling, and make any necessary revisions or suggestions. Following ticket purchase, a final water use plan would be confirmed in accordance with sold ticket volumes and the scheduling needs of all WUAs.

The computer model would help managers prepare, modify, summarize and publish schedules, and could be interrogated quickly by all relevant stakeholders. The model would also help managers deal with the effects of runoff variation and hydrological uncertainty, including emergency planning in the event of floods or droughts.

3.3 Water users associations

A key element of irrigation reform is the promotion of WUAs as farmer run, participatory institutions that take the place of village leader-run water control organisations or government agencies, and take over management of water allocation and infrastructure management at a local level (Wang et al., 2006). Water User Associations are registered as legal entities under Chinese Company Law.

In HID, a total of 43 WUAs have been established since 2000 under 3rd level canals in the gravity flow sections, with a further 40 planned for completion by the end of 2008.. The boundaries of WUAs are defined by areas irrigated by tertiary and fourth canals. As a result, WUA and village boundaries do not always match. HIMB works with WUAs on the development of Annual Water Allocation Plans and scheduling arrangements, and WUAs are obliged to purchase water tickets prior to each irrigation period. It is proposed that WUAs hold and democratically manage GWEs on behalf of farmers and, within capped limits, continue to develop scheduling plans for household members, collect water fees, purchase water tickets from the ID management agency and undertake maintenance work on the infrastructure within their command areas.

The ability of WUAs in Hangjin (and elsewhere in China) to manage water rights effectively under capped GWEs depends on a number of different factors. WET (2007) identify four key pre-conditions, based on a survey of WUAs and farm households conducted in 2007.

Firstly, GWEs-based accounting through water certificates would need to be carefully monitored and enforced. The allocation system in HID combines bulk volumetric charging to WUAs established on branch canals, with area-based charging for farmers. Under such a system, the irrigation district management agency supplies water to WUAs on a contractual basis; contracts have no (current) legal authorization, but do specify the rights and obligations of both the agency and WUAs. Such contracts, or agreements, provide a type of group water right, albeit one of limited security. In Hangjin, moreover, the delivery of water to WUAs is governed by service contracts between WUAs and HIMB. Field work in HID (WET, 2007) suggests that these arrangements provide a sound basis for clarifying rights and responsibilities around water delivery and payment, and for the monitoring and recording of delivery and payment. They are recommended for other irrigation districts embarking on quota-based rights reform.

Secondly, infrastructure needs to be compatible with defined rights and local management capacity. Any discussion on water rights reform cannot be isolated from an understanding of the infrastructure that is available to deliver, monitor and record water flows. In Hangjin, and in most other IDs in China, irrigation systems have not been designed to deliver and record flows to individual farmers. In these circumstances, volumetric rights can only be defined, monitored and enforced down to the level of the WUA and, conceivably, to production teams managing tertiary canals. Hence in such systems it is proposed that capped rights are allocated to WUAs through GWE-based certificates, recognising that farmer-level entitlements cannot (yet) be implemented.

Thirdly, WUAs need well-specified management functions, authority and accountability. A key issue here is whether WUAs genuinely represent the interests of all farmers, and whether they have the capacity to resolve competing claims and disputes. In Hangjin and other IDs where WUAs have been established, the management functions and authority of WUAs are spelt out in a charter, or set of written rules. The ability of farmers to assert individual claims within the bulk GWE will therefore depend on whether WUAs act as genuine organs of democratic self-management, and whether elections required under their charter are held in an open, inclusive and fair way. It is therefore suggested that the democratic management of WUAs is scrutinised closely by the ID management agency for a period of time after initial establishment. Periodic audits of WUA performance covering this and other tasks (e.g. financial book-keeping) are recommended.

Finally, WUAs require adequate resources. A common assumption in irrigation turnover programmes is that WUAs are better (than government agencies) at undertaking water allocation, distribution and fee collection in a cost-effective way. However, new obligations may be a serious burden on WUAs if they have been formed without adequate attention to their ongoing support needs. A key question in Hangjin and other IDs, therefore, is whether pressure to reduce government outlays – a key factor driving management transfer - has extended to an unwillingness to provide sufficient resources for WUAs to retain elected staff and carry out management tasks effectively, particularly in relation to long term water allocation, technical backstopping and maintenance. It is therefore recommended that WUAs are allowed to retain enough ticket revenue to cover the salary costs of their full-time staff, and to cover operation and maintenance tasks within the WUA command area. Resourcing issues could be similarly monitored through periodic audit.

3.4 Water metering and monitoring systems

Many existing monitoring systems in China are crude, and need to be upgraded to support the operation and management of a modern water rights system. In HID, for example, water levels are measured using simple gauges, and flows are measured with traditional flow meters. All measurements are done by hand, with staff having to monitor and regulate flows through over 20 gates to WUAs. In a large ID this creates a very heavy workload for staff and at times of peak water demand, there may be a shortage of manpower.

Future pressure on IDs to release water for urban and industrial users may increase pressure for more accurate monitoring of allocations to WUAs. In this context, automated water monitoring systems may help solve current and future problems, saving labour and money and providing more accurate monitoring and regulation of increasingly scare water.

Design and use criteria a monitoring system needs to meet are outlined below (WET 2007).

- Automated monitoring and data transmission. Automated systems are more accurate and less-labour intensive than manual ones, eliminating the need for station staff to travel between and monitor individual sites.
- Rapid calculation and easy access to data. Data calculation and analysis should be quick and accurate, and data interrogation should be simple and direct. At present, data

enquiries in HID can only be answered by sifting through large numbers of paper records.

- Remote control and monitoring of main sluices. The irrigation management bureau should be able to operate sluices on the main and branch canals at least remotely, avoiding long distance travel for station staff and the need to spend many hours at individual sites.
- Transparency. It is important that an automated system retains the transparency of the existing system. In particular, WUA managers and farmers should have easy access to information on water deliveries to WUAs to build confidence in the quota-based certificate and ticketing arrangements.
- Affordability. Any upgraded system needs to be affordable in terms of both capital costs, and the ongoing costs of repair and maintenance. Benefits can help off-set costs, however, and are likely to include time (labour) savings for irrigation management agency, and water security-income gains for farmers (through more timely and reliable water delivery).
- Durability and security. An upgraded system must be able to cope with the sediment-laden inflows of the river, and not require constant adjustment and maintenance. It should also be equipped with alarms to increase security, and data security and virus protection should be included.
- Ease of use. Advanced systems must be capable of being operated and maintained by station staff.

3.5 An integrated framework for rights management in irrigation districts

Drawing on the discussion above, a broad water rights framework is proposed for HID and other IDs in China. The framework consists of three elements: institutions, irrigation services and regulations. These are described briefly below and illustrated in Figure 3.2.

The institutional component refers to the management institutions responsible for water allocation and delivery, including the relevant river basin management departments, ID management agencies and WUAs. The government river basin management department is responsible for allocating water and issuing water permits to IDs, and auditing their water use plans. No changes to existing allocation arrangements and responsibilities are proposed here.

Irrigation management agencies are mainly responsible for water allocation to WUAs. In this paper, it is proposed that they assume responsibility for the granting and overall management of water rights certificates and water tickets issued to WUAs, in addition to existing responsibilities for collecting water fees, preparing the water use plan of the irrigation district, and monitoring water deliveries to WUAs. Water User Associations, in turn, would assume responsibility for purchasing water tickets within the caps set by GWE calculations, and would manage and monitor allocations under the cap to individual farmers. Field investigations in Hangjin suggest that, where ticket-based payment and contracting systems are already established, the capped arrangements for allocating and purchasing water proposed in this section could be implemented fairly easily.

Irrigation services include the initial allocation of water rights, the issue of water certificates and tickets, water use planning, water delivery and operation of infrastructure. The permitted water abstraction volume of the whole irrigation district is allocated to WUAs through the initial water rights allocation process described, forming the basis for granting water rights certificates and the sale of water tickets. WUAs would purchase tickets within their allocated rights, prepare a water use plan and submit it to the irrigation district management agency for approval. The irrigation district management agency would then complete a water use plan for the whole district and issue delivery instructions to sluice operators, according to each WUAs water use plan and remaining ticket purchase allowance. Deliveries would be monitored and signed-off as they are now, with agency staff and WUA managers entering into seasonal contracts, and jointly monitoring and confirming allocations. The irrigation district management agency would record each WUAs available water, purchased water, and supplied water every year and every watering in their water rights certificates on a continual basis, in order to check the water account and guide water supply in the next period.

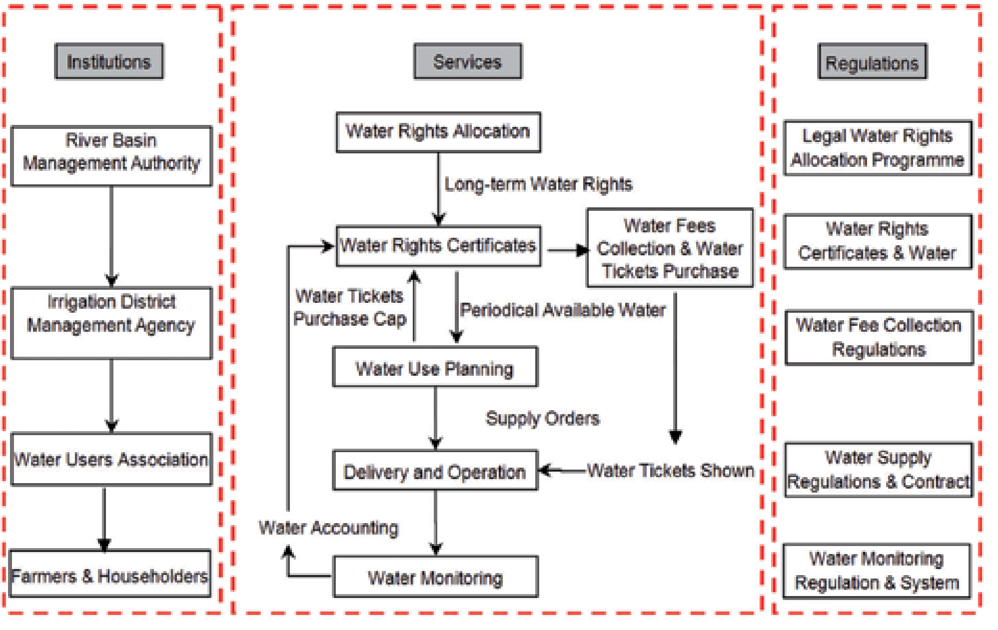


Fig. 3.2 A framework for water rights in an irrigation district

Regulations would then ensure effective implementation and monitoring of the services above, and would need to cover management regulations for the issue and use of water rights certificates and water tickets, water fee collection, water delivery and water monitoring. All management regulations and systems need to be carefully coordinated.

3.6 Recommendations

Based on field investigations in HID, a water rights framework for IDs in China has been proposed in this section, based on an initial water rights allocation, the issue of water rights certificates, sale of water tickets, water use planning and effective management of farmer-level rights through WUAs. Drawing on this framework, the authors offer the following recommendations:

1. Group Water Entitlements should be defined and allocated to WUAs in HID and other IDs, and could additionally be given legal basis by government so that rights can be legally asserted and defended, providing greater security to WUAs and farmers. In addition, a water rights management system should be developed for all IDs, including regulations that cover water use planning, water delivery, emergency planning and risk management, the collection of water fees and maintenance of infrastructure. Entitlement-based allocation planning underpins future water conservation efforts and the development of a modern, socialist countryside of China.
2. The use of an allocation plan to allocate water to WUAs in HID and other IDs is feasible. The annual allocation process in an ID needs to define and allocate GWEs within the overall permitted allowance of the district, determined by the relevant river basin authority. Allocation planning of this kind is fairer and more transparent than existing arrangements.
3. Existing contract and ticketing procedures operating between HIMB and WUAs are well understood and respected. They provide an excellent platform for the introduction of GWEs and ticket-linked water certificates. Those WUAs that have set up systems of continuous water accounting between irrigations, and volumetric delivery to (and billing of) individual production teams, will be better able to meet new quota obligations in a fair and transparent manner. Such systems are recommended for other IDs in China embarking on rights-based reform.
4. Water trading to downstream industrial users has reduced the revenue available to HIMB. The issue of funding will need to be addressed to ensure the long-term sustainability of the trading programme and channel infrastructure, and to protect farmers' long-term water rights. Management and institutional reforms in the ID should be conducted as soon as possible to improve management of the channels, enhance the financial position of the irrigation agency and secure new investment and financial resources. Most importantly, funding for the maintenance of newly lined channels in Hangjin should be secured from industrial enterprises as soon as possible. Similar channel lining and water transfer initiatives being considered by government agencies for other IDs in China need to learn from the experience of Hangjin.
5. Information and monitoring systems in Hangjin and other IDs need to be gradually upgraded to improve accuracy and reliability and reduce manpower requirements. A key priority is to strengthen monitoring of water deliveries at WUA purchase points, as monitoring here affects both WUA payment and compliance with any new system of GWE-based water rights certificates.

4. Water trading among the irrigation districts under a duration-based water rights system

This section introduces a duration-based water allocation system, which has already existed for over 200 years in northwestern China, and discusses a water trading approach in the manners of exchanging the durations (the number of days) for water extraction. As case study in Taolai irrigation district, Gansu Province, China, the efficiency of the inner-agriculture water trading in the duration-based water allocation system is reviewed. This kind of water trading would provide possible approaches to promote water trading in Chinese irrigation district.

4.1 Introduction

Water resources support critical functions within human societies and ecosystems. Along with rapidly increasing population and improved living conditions, urbanization and industrial growth have led to increased demand, competition and conflicts between different water-use sectors (Liu et al., 2009). Climate change will intensify the situation in many parts of the world. It is very important to develop solution strategies to prepare against future conflicts.

The water rights system has been proved an effective tool for water resources management (Wang, 2009; Brook and Harris, 2008). Generally, water rights are defined in volumetric terms, with a statement of the probability that the nominal volume will be delivered in full in any given year (Productivity Commission, 2003). The predictability is a key requirement of a water rights system, so that users can have a reasonable expectation of the volume of water that will be available to them (Speed, 2009). In Australia, the water management authority announces an available percentage of the water rights volume to each stakeholder seasonally according to current reservoir level and inflows over the forthcoming season (Rebgetz et al, 2009). The announcement of the available water should be transparent and least variable to the stakeholders during the year, who thus take the minimum hydrological risk when using water. In the contrary, the water authority takes most of the responsibility for guaranteeing the water rights, which increases its management and technical cost. How to reduce the hydrological risk and to share it between the water manager and users in water allocation is still an ongoing issue, which raised a lot of studies recently both in the developed (Robertson, 2009; Zaman et al, 2009) and developing countries (Wang and Wei., 2006; Zhao et al., 2006; Hu and Tang, 2006; Zheng et al, 2010).

Some useful techniques and methods were proposed in these studies, including the long-term runoff predication, seasonal water allocation, self-adaptive water operation and so on. While all these techniques were developed to provide more reliable water volume availability under a centralized storage management, due to the hydrological uncertainties and storage capacity constraints, the hydrological risk affecting the volumetric water delivery cannot be completely removed only through these techniques. Moreover in practice, it is unlikely that dam managers will have complete information on user's water demand preferences. With this asymmetric information, a central manager may implement a sub-optimal release (allocation) policy, raising a problem that the intra-seasonal allocation is overly conservative, that is, where early season allocations are low and there is unallocated water available in storage (Hughes, 2009).

Institutional innovation such as redefining water entitlements rather than a share of total volume releases (natural stream runoff) is required. A system of allocating property rights to water from shared storages (as well as a share of inflows and losses), which is called capacity sharing, is established in Australia (Dudley and Musgrave 1988, Hughes, 2009). The capacity sharing proposed a decentralize the process allowing individual irrigators to exercise a degree of control over storage decisions and resulted in water entitlements more closely reflecting the physical realities of the water supply system: constrained storage capacity, variable water inflows and significant storage and delivery losses, and thus provided a solution to address the problems outlined above including hydrological risk and asymmetric information.

Similar with the capacity sharing, a Chinese traditional water entitlement may provide another way for solution. China has a long history of water resources development and management. Water diversions for irrigation dated as far back as 316 BC (Wouters et al., 2004). In 18th Century, the administrative water allocation appeared in some arid rivers northwest China by defining the order and length of water extraction period between upstream and downstream users. This kind of water allocation has been widely adopted in the northwest China for hundred years and is still used currently. This traditional water entitlement, instead of sharing the water extraction volume, allocated water rights based on water extraction duration. Each entitlement holder in the river basin is allocated a share of the total number of water extraction days. This water rights arrangement is named "duration-based water rights" in this paper.

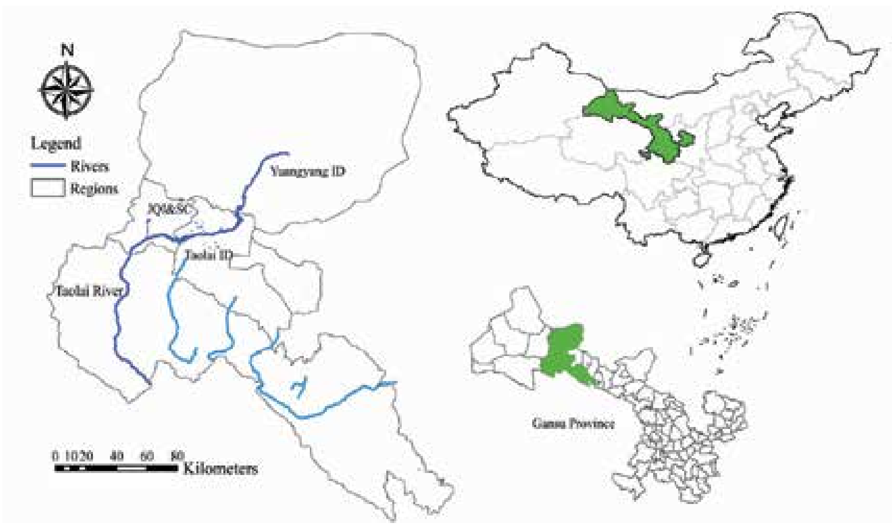
The "duration-based water rights" is defined as a kind of water usufruct which is quantified by the independent duration of water extraction. In "duration-based water rights" system, the water users can store or withdraw the entire natural stream within their permitted extraction period, and manage it independently: determining how much water to use (or sell) and how much to leave in the water course, meanwhile taking all risks from the hydrological uncertainty and variation by themselves. The dam manager does not need to make volumetric allocation announcements and their role becomes in charge of water accounting: recording each user's inflows and withdrawals to monitor the quantity of water in each user's account. However, due to lack of volumetric cap in water use, the surface stream would be likely used out and the ground water would be over extracted in the "duration-base water rights" system.

4.2 Taolai River Basin

Taolai River Basin is an inland watershed located in northwest of China, covers an area of 28,100 km2. The total renewable water resources of the basin are estimated at 1.21 billion m3. It has three main water users: Jiuquan Iron & Steel Corporation (JQI&SC), Taolai Irrigation District (Taolai ID) and Yuanyang Irrigation District (Yuanyang ID) (Figures 4.1 and 4.2). The "duration-based water rights" started in Qing Dynasty about 200 years ago and is still used in this Basin. The stakeholders share the annual water extraction days (365 days in total) in the mainstream of Taolai River: 37 days of water use duration for upstream JQI&SC; 153 days for Taolai ID, and 175 days for downstream Yuanyang ID. These days named as "allocation durations" in this paper are shown as the horizontal length of the slices in Figure 4.3. The users are able to store or use the entire natural stream during their water allocation periods independently, as shown in the right vertical ordinate of Figure 4.3. However, due to lack of volumetric cap in water use in this "duration-based water rights" system, the water resources development ratio in Taolai River Basin is rising and close to 100% recently. An urgent institutional innovation is needed.

4.3 A water allocation-trading framework for duration-based water rights system

An improved "duration-based water rights" system is proposed by (1) introducing the volumetric water use cap in each allocation period, according to the water demand and historical water usage of the users; (2) creating the enabling environment for water trading; (3) promoting the water trading in the valley and (4) setting up an integrated water allocation-trading framework support these improvements (1), (2) and (3).



Note: Data from the National Fundamental Geographic Information System, China.

Fig. 4.1 Location of the Taolai River Basin, Gansu province, China

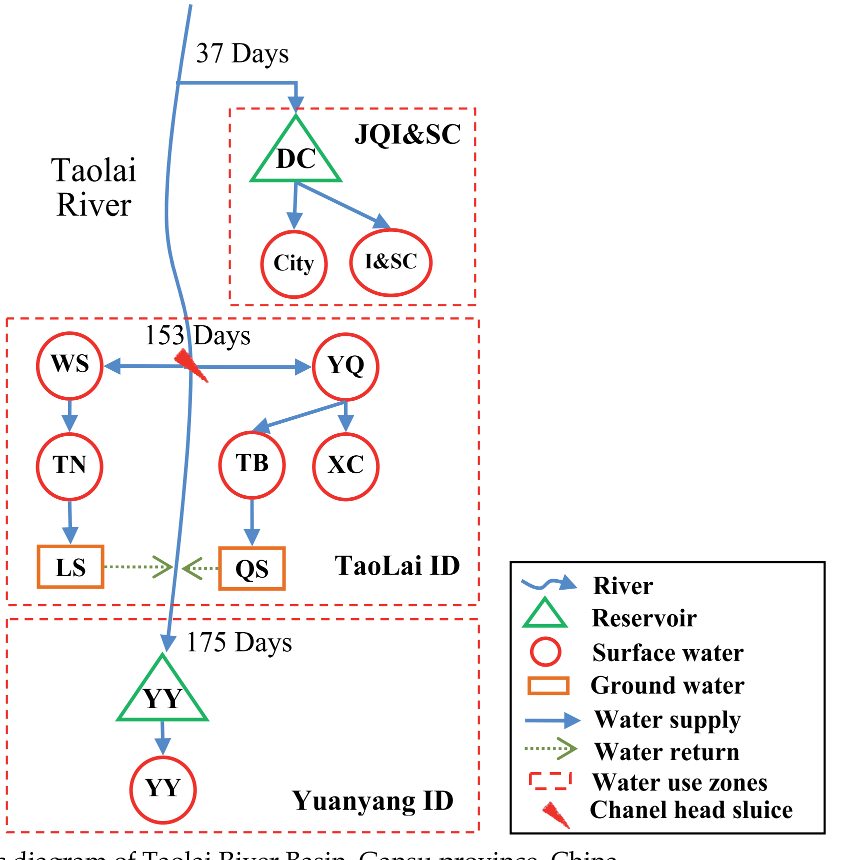


Fig. 4.2 Schematic diagram of Taolai River Basin, Gansu province, China

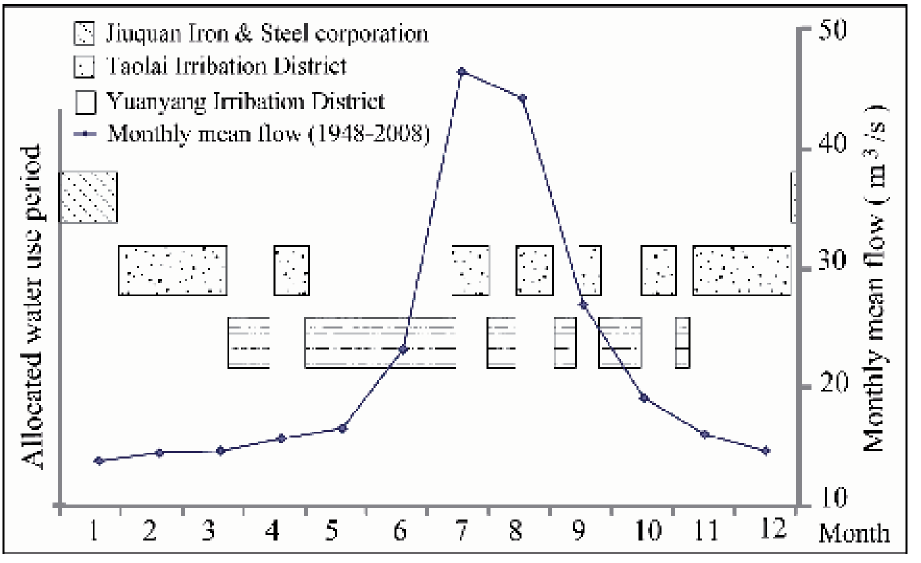


Fig. 4.3 Intra-year allocations of the "duration-based water rights" in Taolai River Basin, China

1. Introducing the volumetric water use cap

The discharge volume within a specific allocation period provides the maximum available water for the user who is authorized to withdraw water in that period under the "duration-based water rights", which is shown in Figure 4.4. The shaded area under the flow curve indicates the available water volume for Yuanyang ID in its first allocation period of the year. The annual available water can be identified by accumulating all the available water in the allocation periods across the year.

The annual available water and historical water use of Taolai and Yuanyan ID under their "duration-based water rights" are shown in Figure 4.5 and Figure 4.6. The water volume is ranked descendingly by the total annual runoff of the Taolai River 1980-2008, and plotted versus the hydrology frequency of the years. The year with hydrology frequency of n% means that the annual runoff of the year will be exceeded in n years out of 100. The annual available water of the IDs is the accessible water within their allocation periods so that is part of the total annual runoff; therefore, the available water in a dry year may be larger than that in a wetter year for the inter-annual variability of the runoff process, which can be found in Figure 4.5 and 4.6.

In Figure 4.5, the historical water use of Taolai ID is stable and less than its available water, which indicates that there is some water didn't or can't be used by Taolai ID in its "duration-base water rights". Actually, this unused water is mainly made up of the flood in July and August, which can hardly be stored by Taolai ID without enough reservoirs in it, and was spill out to the ecosystem and downstream Yuanyang ID. For the ecological benefit from the flood water, involving the stream flow maintenance and groundwater recharge, the annual water use limit is introduced underneath the available water of Taolai ID and portrayed by the upper cap line of historical water use for satisfying the current water demand.

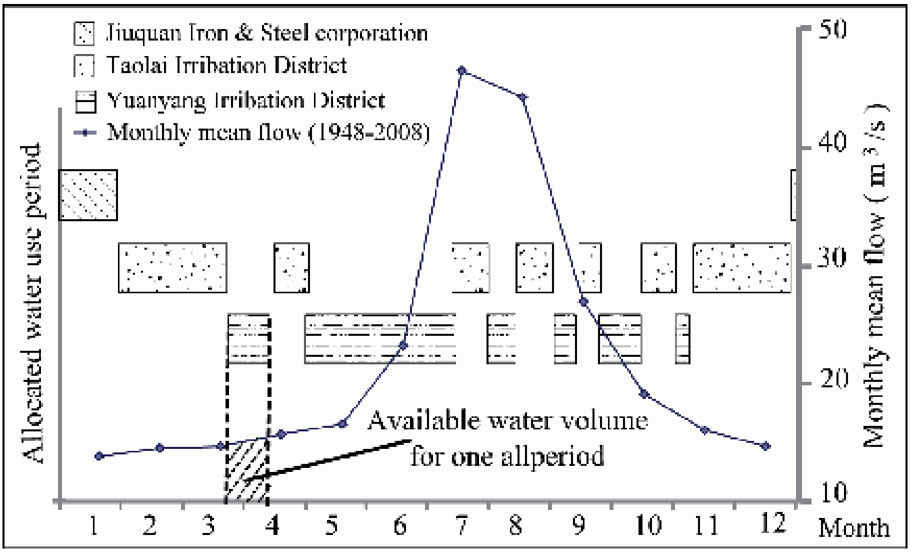
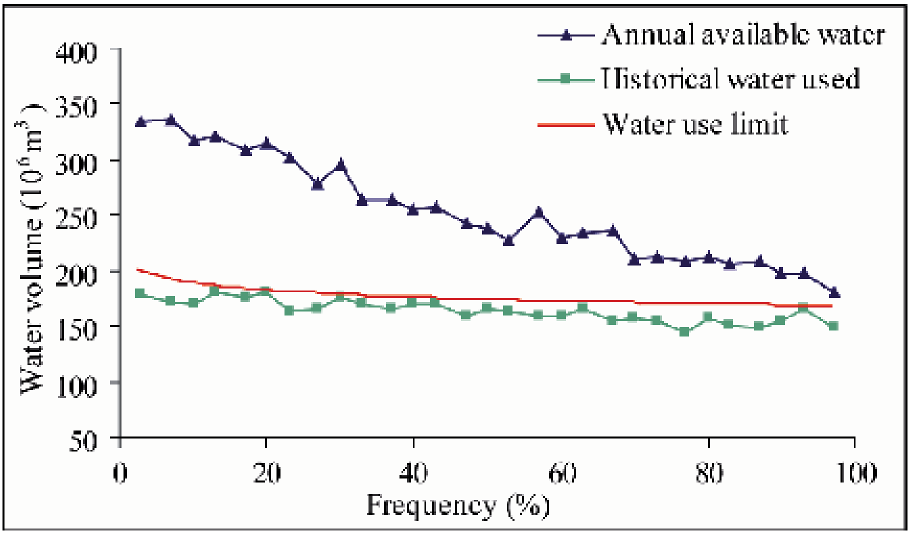
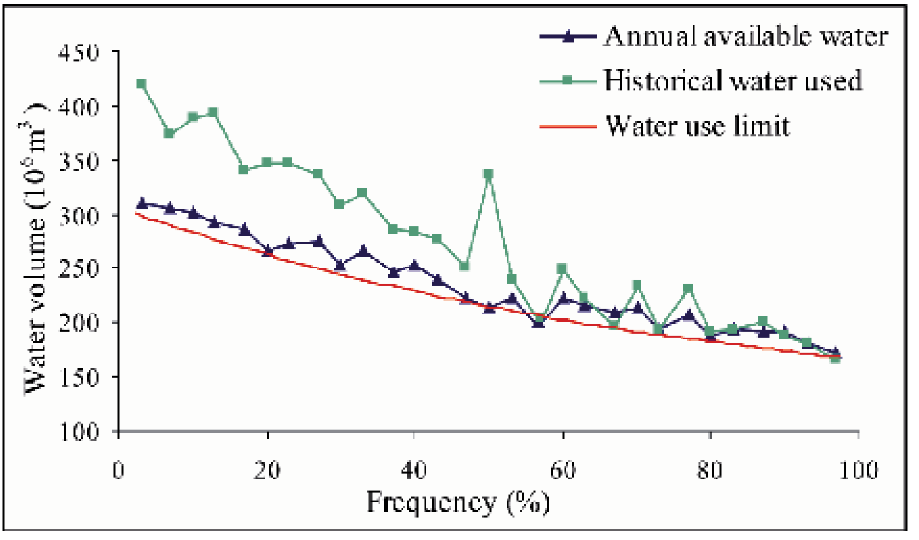


Fig. 4.4 Water available volume in the allocation periods of Taolai River Basin



Note: Source from Zheng, 2011.

Fig. 4.5 Annual available water and water use limit for laolai ID



Note: Note: Source from Zheng, 2011. .

Fig. 4.6 Annual available water and water use limit for Yuangyang ID

In the downstream, Yuanyang ID stored and used part of the flood which was spilled by Taolai ID in its allocation periods, by a large reservoir in it. Therefore, the water used by Yuangyang ID was more than the water available in its allocation periods during 1980-2008. Water use limit of Yuanyang ID is established as the lower cap of its annual available water so that the Yuanyang ID's water extract can follow its "duration-based water rights" strictly and all the flood water can be released for ecosystem, as shown in Figure 4.6.

2. Water use plan and information exchange for water shortage

The objective of water use planning is to schedule water diversion, storage, delivery and use in an ID according to the requirements of farmers, available supply from the river, and flow through the irrigation channel system. A water use plan is a guideline for the rational delivery and use of water within an ID, and can help improve irrigation efficiency and save water (Zheng and et al, 2009). It is proposed that the water use plan takes the water use limits discussed previously as a starting point, and then translates them into a periodical irrigation schedule for water users associations (WUAs) or farmers.

Prior to each irrigation (or allocation period), the period water use plan for the ID would be prepared by the Irrigation Management Agency, based on the plan submitted by each WUA, and submitted upwards through the irrigation agency to the higher-level department for approval, such as the River Basin Management Department, who would then revise and approve the water scheduling of the ID, in term of the water use limit of the ID. Afterwards, the Irrigation District Management Agency would adjust the plan accordingly, and announce it to WUAs and farmers.

If the irrigation water demand is not fully satisfied in the approved plan, on the agreement of the farmers, the Irrigation District Management Agency would release its water shortage information to the valley and search for the water sellers to promote a water trading. This process is proposed to occur through an on-line information exchange system that can balance demand and supply, guide pricing and help manage water trading in a quick and transparent manner, such as the "watermove" system in Australia (Available at https://www.watermove.com.au/Default.aspx).

3. Water trading

The predictability and transferability can be satisfied more strongly in the "duration-based water rights" system due to the stable water allocation periods and the decentralized management of the runoff within them. The economic efficiency of the water trading is described from Equation 4.1 to 4.4.

$$W_a = \int_0^{D_a} Q_a \cdot dt \tag{4.1}$$

$$W_j = \int_0^{D_j} Q_j \cdot dt \tag{4.2}$$

$$MU_a \succ MU_j \tag{4.3}$$

where, W_a and W_j describe the exchanged water volume in April and July between Taolai and Yuanyang IDs (m^3); Q_a and Q_j are mean stream flow in the two months (m^3/s); D_a and D_j are the number of exchanged days. MU_a and MU_j indicate the marginal utility of the water in April and July. From Figure 4.4, it is shown that $Q_a < Q_j$ and $D_a = D_j$. Therefore, $W_a < W_j$ which indicates Taolai ID obtained less water from Yuanyang ID in spring and gave more water back in summer. Due to the serious runoff insufficiency and irrigation competition in spring, the water is more valuable then, as shown in Equation 4.3. So, there is a possibility that the benefit gained by Taolai ID from the allocation period exchange in spring can be equal to its benefit loss in summer. If this balance happens (Equation 4.4), the water trading will be efficient.

$$MU_a \cdot W_a = MU_j \cdot W_j \tag{4.4}$$

In practice, water trading in the manner of exchanging water extraction days between upstream and downstream users has existed in the Taolai River Basin for years. This kind of water trading has being carried out in Taolai River Basin for yeas (totally 10 times, 2005-2009) and reallocated water effectively, with no need of seasonal water allocation, lower transaction cost and thus higher accessibility. In 2008, to solve the upstream water shortage caused by the mismatch between the irrigation schedule and allocation period distribution, the allocation period of Taolai ID was extended in April for 9 days, with the equivalent number of days reduction for Yuanyang ID simultaneously; while in summer when there is excess water for Taolai ID, the allocation period changed in the opposite directions as the same amount of days as in spring, shown in Figure 4.7.

4. Towards an integrated framework for water allocation-trading in the system

Drawing on the discussion above, broad water rights framework, combining the volumetric water use cap and the "time-based water rights", is proposed. The framework consists of three elements: institutions, water allocation-trading services and regulations. These are described briefly below and illustrated in Figure 4.8.

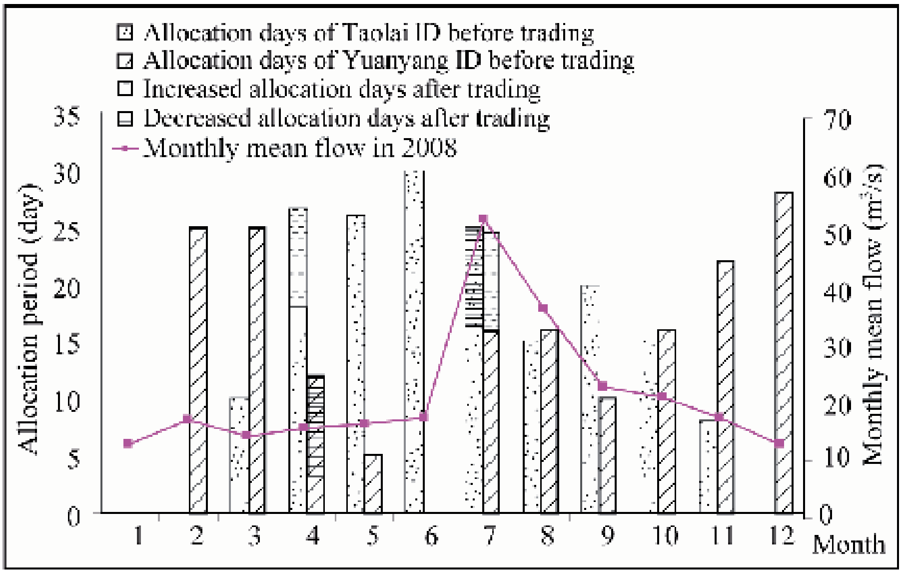


Fig. 4.7 Allocation period exchanges between Taolai ID and Yuanyang ID in 2008

The institutional component refers to the management institutions responsible for water allocation, trading and delivery, including the relevant State Water Resources Management Department, River Basin Management Authority, Irrigation District Management Agency and WUAs. The Water Resources Management Department of state government takes charge of administrative management for River Basin Management Authority. The authority is then responsible for allocating water and issuing water trading permits to IDs, and auditing their water use plans. Irrigation Management Agencies are mainly responsible for water allocation to WUAs and organizing a democratic decision making process for water trading. In this paper, it is proposed that they assume responsibility for preparing the water use plan of the irrigation district, and monitoring water deliveries to WUA. Water User Associations, in turn, would manage and monitor allocations under the cap to individual farmers.

Water allocation-trading services include issue the available water and water use limit, water use planning, water delivery and operation of infrastructure, as well as the information support, application approval, contrast and publicity for water trading. Prior the irrigation, the available water volume and water use limit for current allocation period would be issued to the irrigation district according to the duration of its allocation period and the forecasted runoff. Then, the rationing water volume of the whole irrigation district is allocated to WUAs through the normal volumetric water allocation process, providing the cap for water use planning of the WUAs. The Irrigation District Management Agency would then complete a water use plan of the whole district accordingly and check whether there are water shortage and the necessity for buying water. After the democratic consultation with farmers, if the irrigation district decides to buy some water and extend its allocation period, the management agency would publish its requirement to other irrigation districts and seek the water seller. If the buyer and seller get an agreement on water trading, they would submit a trading application to the River Basin Management Authority for approval.

The water trading will be legally effective only after the trading application is approved by the government and passed through by publics.

Regulations would then ensure effective implementation and monitoring of the services above, and would need to cover management regulations for the issue and use of volumetric water use cap together with the "duration-base water rights", and the information exchange, decision making, third-party impacts assessment and approval for water trading, as well as water delivery and water monitoring. All management regulations and systems need to be carefully coordinated.

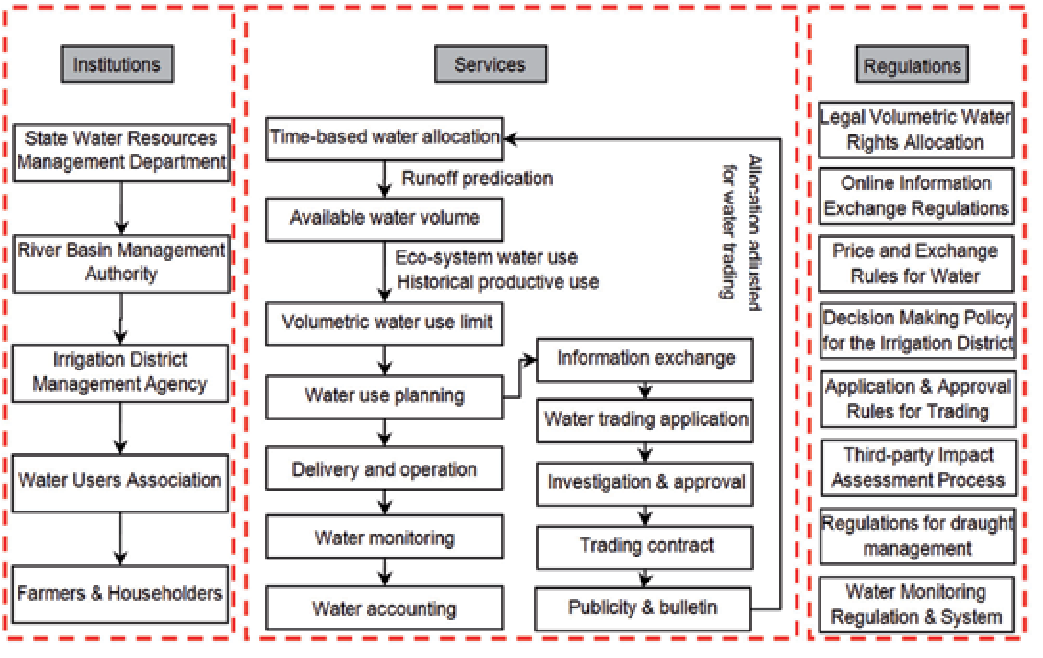


Fig. 4.8 Water allocation-trading frameworks for duration-based water rights system

4.4 Recommendations

A water allocation-trading framework based on the "duration-based water rights" was proposed in this section. Comparing with the normal volumetric water rights system, the framework is supposed to reduce the management cost of the water authority by introducing a decentralised and semi-independent water management to the stakeholders. In the framework, water entitlement is indicated by the fixed amount of water extraction days and would hardly be affected by the hydrological uncertain. The water users can manage the stream flow and storage independently during their allocation period under the volumetric water use cap. The water authority is just responsible for the water use planning and accounting, making sure the water use of the stakeholders not over their limit. The hydrological risk is shared mostly by water users while they get more flexibility to make their own storage decisions, taking into account their private information on water needs.

The idea of "duration-based water rights" is similar with the capacity sharing in Australia to a certain extent. Capacity sharing is a system of allocating property rights to water from shared storages proposed by Dudley (Dudley and Musgrave 1988, Dudley and Alaouze 1989, Dudley 1990, Dudley 1992). Each entitlement holder in an irrigation system is allocated a share of the total system storage capacity, as well as a share of total inflows (spill water and losses). Users are able to manage these capacity shares independently, as well as take the hydrological risk and losses. The duration-based water allocation-trading framework suggests a property rights system by sharing the water extraction duration, rather than storage capacity. But both of the systems suggest a decentralize the process by designing some system of property rights allowing individual irrigators to exercise a degree of control over storage decisions, which is helpful to address some of the problems of centralized water management, such as the hydrological risk, asymmetric information and transaction costs in water delivering. The proposed duration-base water allocation framework could provide a comparison reference for capacity sharing, and the success of the capacity sharing practice in Australia could be helpful to understand the feasibility and practicability of the proposed framework.

Volumetric water use limit was introduced and combined with duration-based water allocation in the study, which suggested a mechanism to integrate the international contemporary water rights system with the Chinese traditional water management. In recent decades, with the introduction of the global experiences of water rights reform, volumetric water right and its allocation system have been implemented across the China to a varying degree (Gao, 2006; Shen & Speed, 2009), and replaced the traditional water allocation system in most of the rivers. This has raised many conflicts in the reforms. The integrated mechanism proposed in this chapter would be helpful to buffer the conflicts when establishing a volumetric water rights system in valleys where the traditional water allocation is still working. Moreover, the integrated water allocation-trading framework could be used in the upcoming process of establishing the water market in Taolai River Basin, which would probably become the first water market in China and also a significant improvement in China's water rights reform. The framework would be feasible for the arid river, especially the valley which has uneven spatial distribution of the storage capacity.

For the limitation of the data and practices, the proposed framework just provides a conceptual framework of integrating the volumetric and time-based water rights without enough data verification. As noted, to transform this result based on one case study into the business of managing water catchments on a daily basis requires considerable further research, policy development and investment. Some future researches are still required to improve the framework, involving (1) defining the volumetric ground water cap in Taolai valley; (2) pilot study to verify the feasibility and validity of the framework; (3) modelling the irrigation water use planning which is constrained by the volumetric cap and time-based allocation in the irrigation districts and farmers level; (4) the technique for monitoring and accounting the water use and trading volume.

5. Acknowledgment

The study is supported by National Natural Science Foundation of China (51009076); International Science and Technology Cooperation Program of China (2010DFA21750); the project of "a framework for integrating the traditional water allocation and modern management" funded by water resources management department, Gaunsu Province, China; and the China Environment Development Program- Shiyang/Shule River Project as well as the 2011 Chinese Ministry of Water Resource Program - Shiyang River Project (201101046).

6. Reference

Babel, M. S.; Gupta, D. A. & Nayak, D. K. (2005) A model for optimal allocation of water to competing demands, *Water Resour. Management*, No.19, pp. 693–712.

Yellow River Conservancy Commission. (2005). Decree on Yellow River Water Resources Regulation Available from: http://www.yellowriver.gov.cn/ziliao/zcfg/fagui/200612/t20061222_8784.htm (21 December 2008).

Dudley, N. & Musgrave, W. (1988) .Capacity sharing of water reservoirs, *Water Resources Research*, No.24, pp. 649-658.

Dudley, N. (1990) *Alternative institutional arrangements for water supply probabilities and transfers*. Centre for Ecological Economics and Water Policy, University of New England, Armidale, NSW, Australia.

Dudley, N. & Alaouze, C. (1989) Capacity sharing and its implications for system reliability, Proceedings of the National workshop on Planning and Management of Water Resource systems, *Australian Water Resources Council Conference Series*, No. 17, 1989.

Dudley, N. (1992). Water allocation by markets, Common property and capacity sharing: Companions or Competitors? *Natural Resources Journal*, Vol.32, No. 4, pp: 757-778.

Feng, E. & Li, X. (2006). The study on the water rights system in the irrigation districts in the inland river basin, *China, Gansu Agricultural University Journal* [in Chinese] No.2, pp. 105–108.

Gao, E. (2006). *Water Rights System Development in China,* Beijing: China Water and Hydropower Publisher. [In Chinese]

Hayman, P.; Crean, J.; Mullen, J. & Parton, K. (2007). How do probabilistic seasonal climate forecasts compare with other innovations that Australian farmers are encouraged to adopt? *Australian Journal of Agricultural Research*, No.58, pp. 975-984.

Hu, J., & Tang, D. (2006). Study on the updating management of water right of Tarim River Basin. *Yangtze River*, No.37 (11), 73-75. [In Chinese]

Hughes, N. (2009) Management of irrigation water storages: carryover rights and capacity sharing, *Australian Agricultural and Resource Economics Society Conference Paper*, Cairns Queensland, 11-13 February.

Inner Mongolia Water Resources and Hydropower Survey & Design Institute (2005) *Inner Mongolia Autonomous Region Water Rights Transfer Planning Report* [in Chinese], Technical Report.

Liu, D.; Chen; X. & Lou, Z. (2009) A model for the optimal allocation of water resources in a saltwater intrusion area: a case study in pearl river delta in China, *Water Resour. Management*, No.24, pp.63-81.

Productivity Commission. (2003). Water rights arrangements in Australia and overseas. Commission Research Paper, Melbourne: Productivity Commission, pp: XIV.

Qureshi, M. ; Shi, T. & Qureshi, S. et al. (2009). Removing barriers to facilitate efficient water markets in the Murray-Darling Basin of Australia, *Agricultural Water Management*, NO.96, pp. 1641-1651.

Robert, B. & Edwyna, H. (2008). Efficiency gains from water markets: empirical analysis of Watermove in Australia, *Agricultural Water Management*, No.95, pp. 391-399.

Rebertson, D.; Wang QJ. & McAllister, A. et al. (2009). A Bayesian network approach to knowledge integration and representation of farm irrigation: 3 spatial application. *Water Resource Research*, No.45, doi:10.1029/2006WR005421.

Rebgetz, D.; Chiew S. & Malano H. (2007). Forecasts of seasonal irrigation allocations in the Goulburn Catchment, Victoria. The Modelling and Simulation Society of Australia and New Zealand Inc papers.

Shen, D. (2004). The 2002 Water Law: Its impacts on river basin management in China, *Water Policy*,No.6, pp. 345–364.

Shen, D.; Sheng, X.; Wang, R. & Liu, A. (2006) .Water rights reform in Inner Mongolia, China, *China Water Resource* [in Chinese], No.21, pp. 9–11.

Shen, D. & Speed, R. (2009) Water resources allocation in the People's Republic of China, *International Journal of Water Resources Development*, Vol. 25, No. 2, pp. 209–225.

Speed, R. (2009) A comparison of water rights systems in China and Australia, *International Journal of Water Resource Development*, Vol. 25, No. 2, pp. 389-405.

Wang, G. & Wei, J. (2006). *Water resources operations model in a river basin and its application*. Science Press, Beijing, China, pp. 109-112. [In Chinese]

Wang, X.; Huang, L. & Rozelle, S. (2006). Incentives to managers or participation of farmers in China's irrigation systems: which matters most for water savings, farmer income and poverty? *Agricultural Economics*, No.34, pp. 315–330.

Wang, ZJ.; Zheng, H. & Wang X. (2009) A harmonious water rights allocation model for Shiyang River Basin, Gansu Province, China, *International Journal of Water Resources Development*, Vol. 25, No. 2, pp. 355-370.

WET (2007) Water Entitlements and Trading Project (WET Phase 2) Final Report December 2007 [in English and Chinese] (Beijing: Ministry of Water Resources, People's Republic of China and Canberra: Department of the Environment, Water, Heritage and the Arts, Australian Government). Available from http://www.environment.gov.au/water/action/international/wet2.html.

Wouters, P.; Hu, D.; Zhang, J.; Tarlock, D. & Andrews-Speed, P. (2004). The new development of water law in China, *University of Denver Water Law Review*, Vol. 7, No.2, pp: 243–308.

Wu, D. & Wu, Z. (1993). On water use planning and water tickets, *Water Economy*, No.8, pp. 50–52. [in Chinese]

Xie, J. (2008). *Addressing China's Water Scarcity: A Synthesis of Recommendations for Selected Water Resource Management Issues* Washington, DC: World Bank Publications.

Zaman, A.; Malano. H. & Davidson B. (2009) An integrated water trading-allocation model, applied to a water market in Australia, *Agricultural Water Management*, No.96, pp. 149-159.

Zhang, C. & Wang, Z. (2004). The quantitative evaluation of human activities in Hei River Basin. *Earth Science*, No.29, pp. 396-390. [In Chinese]

Zheng, H.; Wang, ZJ.; Liang Y. & Roger C. (2009). A water rights constitution for Hangjin Irrigation District, Inner Mongolia, China, *International Journal of Water Resource Development*, Vol. 25, No. 2, pp. 371-385.

Zheng H.; Wang ZJ. & Hu S. (2010). A real time operation model for water rights management, *the 5th International Symposium on IWRM and 3rd International Symposium on Methodology in Hydrology*, Najing, China.

Zheng H.; Wang ZJ. & Hector M. et al. (2011). A water allocation-trading framework for duration-based water rights system in China, *Agriculture Water Management*, under review.

Zhao, Y.; Pei, Y.; & Yu, F. (2006). Real-time dispatch system for Heihe River basin water resourc. *Journal of Hydralulic Engineering*, Vol. 37, NO. 1, pp. 82-88. [In Chinese]

Zhou, W. (2001) The irrigation and water saving method in northwest China. *Advances in Water Resources and Hydropower*, Vol. 21, No. 1, pp. 1-4. [In Chinese]

5

Effects of Irrigation-Water Pricing on the Profitability of Mediterranean Woody Crops

M. A. Fernández-Zamudio[1], F. Alcon[2] and M. D. De-Miguel[2]
[1]Valencian Institute of Agricultural Researchs
[2]Technical University of Cartagena
Spain

1. Introduction

Tree-crops play a fundamental role in Mediterranean Spanish regions. Irrigated farmlands of citrus and a wide range of fruit-trees are characteristic of the Valencian Community and the Region of Murcia, for instance. These are intensively grown crops whose production is destined for fresh consumption, and are highly competitive due to the large proportion that is exported. However, there are other crops commonly grown in the inland areas which, although not weighty in economic terms, are of major importance. Examples are the irrigated table grapes, olives, almond trees and vines which are grown mostly under dry or rainfed conditions. The latter are paramount in the settlement and permanence of the rural population, especially in regions where agriculture remains the economic mainstay. Furthermore, management is also highly environmentally sustainable, because these crops consume minimum amounts of water. In this chapter these four species have been chosen to represent the Spanish Mediterranean woody crops.

In recent decades, socioeconomic and political changes have led to a clear transformation of the farming communities in the Mediterranean regions. Both the industrial and the service sectors continue putting strong pressure on labour resources, especially among young people, which limits generational take-over and leads to the disappearance of family farms, giving little incentive to continue farming activities.

The climate in these Mediterranean areas is characterized by short, mild winters, hot summers and, in many areas, with an annual precipitation below 300 mm, making water the scarcest and most valuable natural resource in these regions. Thus, the aquifers are subject to excessive extraction, often resulting in poor water quality. Main crop production can only be guaranteed with some type of irrigation. Official markets of irrigation water have not been developed yet, but in producing regions the resource is exchanged; it is especially common that growers administer their allocation and divert it to more profitable plots. This propitiates marginal management, where a plot is maintained during a period with only basic cultural practices.

To encourage a sustainable use of water in agriculture, the recently entered into force European Water Framework Directive (WFD) proposes the full cost recovery related to water services under the polluter pay principle. For this end, a water pricing policy should be established by Member States and, it is foreseeable that the price of irrigation water will increase in such a way that the final price of irrigation water to be paid by the grower will cover all of the costs (economic and environmental) incurred in delivering it. But the field prices of most agricultural products are increasingly lower, and any increase in production costs may seriously affect its feasibility.

In this context, the objective of this study is to analyze the potential trend of certain Spanish Mediterranean woody crops, on the establishment of tariff policies that differ from those currently implemented. To achieve this goal, the water demand curves obtained for olives, vineyard, almond trees and table grapes have been analyzed. The results will enable policy makers and water resource managers to be informed of the effect that the introduction of a pricing policy would have on Mediterranean agriculture influencing decision making, taking into account the environmental objectives of the WFD while maintaining the social and environmental benefits of traditional farming in the Mediterranean regions.

The remainder of the chapter is organized as follows. In the next section, the economic analysis of irrigated water use is reviewed, as well as the main methodological approach. In sections 3 and 4 two case studies are analyzed. Finally, general conclusions are drawn.

2. Analysis of irrigation water pricing on Mediterranean crops

2.1 Background

Water is becoming an increasingly scarce resource in the world due to population growth, improved quality of life and diminishing resources. Thus, efficient allocation of water becomes increasingly important and must be achieved if we are to reconcile economy and society, because water management is often guided by contradictory aims. Furthermore, to achieve efficient water management, given the competitiveness of demand, it will be necessary to consider the distribution of wealth among different users, and ensure the right to access to water following environmental criteria that enable ecological sustainability. Therefore, those responsible for water management require broad vision, taking into account the results of different water management policies, and also to learn how to select the specific management tools for each situation.

Numerous papers are found in scientific literature that determine the economic effects of the application of different water policies or the adoption of one type of irrigation system or another. Works related with irrigation water management in Mediterranean crops are: Gurovich (2002) studied the energy cost of irrigating the Chilean table grape; Hearne and Easter (1997) analyzed the impact of applying water markets to the cultivation of fresh grapes; Bazzani et al. (2004) investigated the effects of putting into practice the Water Framework Directive in Europe; Jorge et al. (2003) carried out an economic evaluation of the consequences of drought on the Mediterranean crops; and Fernández-Zamudio et al. (2007) obtained irrigation water demand curves for the Spanish table-grape.

The WFD sets out a strategy for general water management and establishes environmental objectives for water bodies in order to achieve a so-called "good ecological status". To achieve these objectives in innovative ways, the WFD prescribes using economic tools and principles, among which is the principle of full cost recovery related to water services. The incorporation of this principle will lead to member states restructuring existing water rates to allow recovery of full costs of water services, including both the environmental and the resource. In this sense, water pricing policies are viewed by the WFD as a way to internalize the costs so they can educate users about water shortage.

Economic theory sets that farmers would respond to an increase in water prices by reducing their consumption, in accordance with a negative slope demand curve. Thus, the implementation of water pricing measures would create incentives to use water efficiently and, in accordance with the WFD, would contribute to the achievement of environmental objectives. It is believed that the use of suitable water pricing policies would encourage users to limit their water use (Easter and Liu, 2005).

However, the tariff policy applied must consider the specific conditions of each irrigation area, since its effect will be very different depending on their characteristics. Specifically, in south-eastern Spain, where the irrigation water demand curve is usually inelastic, a tariff policy would be valid only from the standpoint of cost recovery, but is not expected to be so from the water savings perspective (Sumpsi et al., 1998; Varela et al., 1998).

Up to our knowledge, the impact of the water pricing policy in Spain was firstly analyzed in three irrigated areas by Berbel & Gómez-Limón (2000). They applied a simple lineal programming model to analyze the impact of using a volumetric water policy instead of an area pricing scheme on agricultural production. They found that demand curve become inelastic and inefficient for a water prices higher than 0.15 €/m^3, concluding that volumetric water pricing would have undesirable consequences over the farm income and the employment, reducing also the range of crops available.

Two years later, after WFD entered into force, Gómez-Limón et al. (2002) study both the impact of the cost recovery principle proposed by the WFD and the effect of the common agricultural policy on agricultural irrigation systems using multi-criteria techniques (multi-attribute utility theory). They used an irrigation community, placed in the north-central of Spain (*Bajo Carrión*, Palencia), and they found that the inelasticity of the water demand curve is reached from 0.09 €/m^3. From this value it is concluded that an increase of water price would not influence the amount of water demanded. Also, in this irrigation community, Gómez-Limón & Berbel (2000) derive water demand function using weighted goal programming approach obtaining that water pricing policies are not a satisfactory tool for significantly reducing water consumption in agriculture. They argued that water consumption is not reduced significantly until prices reach such a level that farm income and agricultural employment are negatively affected.

In this line, and using a multiattribute utility theory (MAUT) mathematical programming models, Gómez-Limón & Riesgo (2004a) analyzed the impact of the hypothetical implementation of recovery of costs water pricing proposed by the WFD on three homogeneous groups of farmers in the irrigation community *Virgen del Aviso*, in the north of Spain. They found again that the effect of irrigation water pricing vary significantly depending on the group of farmers being considered, being the demand curve of the group with higher ability to pay for the water inelastic from 0.12 €/m^3. The same methodology was also applied in an irrigation community of the *Pisuerga channel*, in the north of Spain by Gómez-Limón & Riesgo (2004b) obtaining similar findings.

In general, the works quoted above analyze irrigation water demand curves in irrigation communities of Spain, and all of them have been applied to irrigated areas with a predominance of extensive arable crops. These crops, which represent a majority in Spain, have a yearly production cycle and their production margins are very similar. These characteristics contribute to the replacement of one species by another depending on the harvests. However, it is expected that woody crops show different behaviour than extensive crops due to the higher investment costs and the time needed to recover such investment. Recent studies, such as that by Mesa-Jurado et al. (2010), determine the marginal value of irrigation water in a woody crop, like the olive tree, in a sub-basin the Guadalquivir River Basin using production function based on field experiments. Net marginal values of water obtained from the marginal benefit curve (having deducted the variable costs of production including harvesting and irrigation) were 0.60 and 0.53 €/m^3 for an allocation of 1,000 and 1,500 m^3/ha respectively.

For the whole Guadalquivir River Basin, a wider analysis of the demand of water has been estimated by all irrigated crops, extensive and perennial. This work has been carried out by Berbel et al., (2011) using the Residual Value Method. This technique is based on the idea that a profit-maximizing firm will use water up to the point where the net revenue gained from one additional unit of water is just equal to the marginal cost of obtaining the water. An approximation to the demand curve can be obtained plotting the average residual water values aggregated for all crops by area and the water consumed by this area. In this work, where citrus and olive tree are considered jointly with extensive crops, the residual water value is estimated between 0.01 and 0.68 €/m^3. The high residual water values are explained for the existence of woody crops.

Thus, from the analysis of the previous works it is possible to identify that the demand of water for wood crops seems more inelastic than for extensive crops, due to for small allocation the price is highly valuable, being the marginal water prices of woody crops considerable higher. Studies that analyze the establishment of tariff policies on woody crops are still scarce, and more research based on this kind of crops would contribute to fill this gap of knowledge.

2.2 Methodology for analysis of irrigation water pricing

In order to deduce the effects that irrigation water availability and price have on the viability of the main rainfed tree crops grown in Spain as well as table grapes and the woody crops representative of irrigated farmlands in the Mediterranean region, several mathematical calculations have been used in this work. Together with the calculations of shadow prices and irrigation water demand curves, the maximum price that farmers can afford for water resources has been obtained.

The shadow price of irrigation water is the value corresponding to the opportunity cost of having one more cubic meter of water on the farm. The economic impact that is expected from having more water available, for which the approximate value of irrigation water is cited as Euros per cubic meter. This price cannot be considered the actual price that the farmer may pay for the water resource and it must be inferred from the demand curves.

To calculate shadow prices a quantitative analysis has been carried out using the Compromise Programming (CP) technique belonging to the multicriteria paradigm.

Usually, the analyzed objectives in multicriteria models are in conflict with each other, and therefore, to optimize the different objectives simultaneously and achieve an ideal solution is impossible. However, it is possible to determine the small group of effective points that bring us closest to that ideal, which would be the solution in which all the objectives reach their optimum value (Romero & Reheman, 2003). The mathematical essence of this calculation was established by Zeleny (1973) and Yu (1973), and a number of authors have used this technique in agriculture. For example, Sabuni & Bakshoudeh (2004) used the CP to determine the opportunity cost of water on farms, or Ballestero et al. (2002) who analysed the establishing of water markets.

The CP is one of the most commonly applied multicriteria techniques due to its high operativity (Romero & Reheman, 2003), and it is associated with the concept of distance, though not in the geometric sense, but rather the distance or degree of proximity from the ideal. This distance (d_j) of the objective $f_j(x)$ with respect to the ideal f^*_j, will be written:

$$d_j = \left| f_j^* - f_j(x) \right| \tag{1}$$

Normally the objectives have very different absolute values or they are measured in different units, therefore before adding the degree of proximity they could all have, one must carry out a dimensional homogenization, giving:

$$d_j = \frac{\left| f_j^* - f_j(x) \right|}{\left| f_j^* - f_{*j} \right|} \tag{2}$$

where f_{*j} is the worst value of the objective when it has been optimized separately and called the anti-ideal value.

Likewise, in the calculation, one must also consider the preferences that the decision centre can show for each objective, for this reason a weight w_j is included. All this means that the effective solutions that come closest to the ideal are achieved by resolving the following optimization problem:

$$Min\ L_p = \left[\sum_{j=1}^{n} w_j^p \cdot \left| \frac{f_j^* - f_j(x)}{f_j^* - f_{*j}} \right|^p \right]^{1/p} \tag{3}$$

Subject to $x \in F$, where x are the decision variables, F is the set of restrictions of the model, n is the number of the objectives introduced in the modelization and p the metric (Romero & Rehman, 2003).

The points that fall closest to the ideal (called the compromise set) can be bounded between the metrics one and infinite, in other words L_1 and L_∞ (Yu, 1973), which is considered acceptable, even though there are more than two objectives. The economic significance of these solutions is connected with the traditional optimization based on utility functions and L_1 indicates the value of greatest efficiency, while L_∞ is the solution with greatest equity (Ballestero & Romero 1991).

For the demand curves, the Multiattribute Utility Theory (MAUT) has been widely founded. The work by Keeney & Raiffa (1976) is a starting point of the MAUT. In essence it consists of being able to establish a mathematical function U, which encompasses the utility resulting from a series of attributes, which are previously considered according to the importance each of them has for the decisor. This theory starts from strict mathematical requirements; however, the works by Edwards (1977) or Huirne & Hardaker (1998) show that, although these are not strictly satisfied, one can obtain utility functions that are extremely close to the true utility.

In order to estimate the additive utility functions, the framework developed by Sumpsi et al. (1996) and Amador et al. (1998) has been followed, and later applied by Gómez-Limón et al. (2004). First one calculates the pay-off matrix, and then resolves the following system of $n+1$ equations:

$$\sum_{i=1}^{n} w_i f_{ji} = f_j \tag{4}$$

for $j = 1, 2, ..., n$ and $\sum_{i=1}^{n} w_i = 1$

With n being the number of objectives considered, w_i are the weights of the different objectives (and therefore, unknown), f_{ji} are the elements of the payoff matrix, corresponding to the values reached by the objective of column-i when the objective of row-j is optimized. Finally f_j is the value of the j-th objective in accordance with the distribution of the crops observed.

If the above system of equations has a non-negative solution, then w_i indicate the weights of the different objectives, but this is not usually the case, as there is no set of weights that reproduce the farmers preferences with precision. To approximate the said solution as far as possible, one minimizes the sum of m_j and p_j , for which the following lineal program is resolved:

$$Min \sum_{j=1}^{n} \frac{m_j + p_j}{f_j} \tag{5}$$

subject to:

$$\sum_{i=1}^{n} w_i f_{ji} + m_j - p_j = f_j \quad \text{for } j = 1, 2, ..., n$$

$$\sum_{i=1}^{n} w_i = 1$$

with m_j the variable of negative deviation and p_j the variable of positive deviation. According to Dyer (1977), the weights obtained previously, coincide with the following expression of the utility function, which is separable, additive and lineal for each attribute $f_i(x)$,

$$U = \sum_{i=1}^{n} \frac{w_i}{k_i} f_i(x) \tag{6}$$

where k_i is a normalizing factor, for instance the difference between the best or ideal value for each objective, f_i^*, and the worst or anti-ideal, f_{i*}, which are extracted from the pay-off matrix, with the additive utility function finally being expressed as:

$$U = \sum_{i=1}^{n} w_i \frac{f_i(x) - f_{i*}}{f_i^* - f_{i*}} \tag{7}$$

The utility function it is assumed that the farm owners will maintain their psychological attitude with regard to decision taking for a short to medium term. From this point the study goes on to look at a series of simulations with rising prices of irrigation water, in such a way that, each price is a new scenario in which utility is maximized, and from which a cropping plan is derived with a specific demand for irrigation water.

3. Case 1: Rainfed Mediterranean tree crops (olive, vineyard and almond): Response to variations in irrigation water pricing

Spanish Mediterranean dry-farming is predominant in the large inland extension, and the most traditional and characteristic crops are the olive (*Olea europea*), the vineyard (*Vitis vinifera*) and the almond (*Prunus dulcis*). All of them are shared in the farms in different proportions. These crops have helped in maintaining the countryside, which is one of the marks of the cultural identity of these regions, protect the soil from erosion, and they can also be considered an important promoter of human activity.

In the arid regions of the Mediterranean, agriculture is strongly conditioned by the irregularity of the climate, specially the rains. The most important natural resource is water, which is in short supply and of the greatest value. Consequently, the availability of water for irrigation significantly increases cropping yield, assures a greater regularity in harvest, and decreases the economic risks in farming.

The size of the farm also exerts an influence, but in contrast to the small-holding structure that is characteristic on the coast, in these inland regions the land is not considered as such a restrictive factor, and normally, it is rather the lack of family labour needed to cultivate the farm in optimum conditions that leads to marginal management. “Marginal management” defines non-definitive semi-abandonment, in which these three tree crops survive left to the mercy of the climate. This is often the case in the regions under study and at specific periods of time when, due to the lack of labour or profitability, the farmers do not optimize crop care and limit it to a minimum (Fernández-Zamudio et al., 2006).

3.1 The most outstanding traits of the dry regions

The present study focuses on the Valencian Community, where dry-lands account for 56% of this area. Here the olive, vineyard and almond are the most extensive crops, representing 35% of the worked lands in this region (CAPA, 2011). These three crops can be cultivated in strict dry-farming or with irrigation at very specific moments (irrigated relief), considered as essential to ensure harvest, and in the case of the vineyard and olive conventional drip irrigation is also possible, with greater and more continuous flow.

In order to determine the optimal cropping plans in the Mediterranean cropping dry-land, the following objectives have been chosen: one of economic nature (to maximize profits), another social (minimization of total annual workforce) and the other environmental (minimization of irrigation water consumption). The mathematical expression of these three objectives is:

$$Max \sum_{i=1}^{n} NM_i \cdot X_i \tag{8}$$

$$Min \sum_{i=1}^{n} Q_i \cdot X_i \tag{9}$$

$$Min \sum_{i=1}^{n} TL_i \cdot X_i \tag{10}$$

Where NM_i is the net margin of the activity i, X_i is the surface area, Q_i is the annual irrigation water supplied and TL_i is total labour employed annually.

3.2 Information and methodology

Family farms predominate in the Mediterranean inland regions; therefore, the analysis is carried out choosing a representative farm, with 32 hectares of land and a full-time family Agricultural Work Unit (AWU). Within the Valencian Community, the study was located in the *l'Alcoià* area, in Alicante province. This is a region with a semi-arid climate, with the risk of frost from November to March, and 474 mm of average rainfall per year. In this region there are two zones that are very different in terms of slope, but the risk of natural erosion is considered moderate. The irrigation water mainly comes from private wells, and a small proportion distributed by the Irrigation Community of the River *Vinalopó*.

The calculations have been applied to two modelization scenarios that are real in these regions, and the differences are exclusively in the degree of mechanization existing on the farm. In the "manual-scenario" low-powered mobile equipment was used together with traditional harvesting and hand-picking, and in the "mechanized-scenario" higher-powered mobile equipment is considered.

In this study the decision variables, or unknowns of optimization, are the surface area in farm for each crop-growing activity. Olive, vineyard and almond, which are most characteristic of the region, have been introduced, being the main difference the amount of irrigation water (Table 1). To calculate the net margin of an activity, the variable costs, which include hired labour and the fixed costs are subtracted from the income earned through selling the production -together with the subsidy if there is one. In calculating the income, the average production for each crop-growing activity was fixed according to the data taken in the region and after validating them with experts. In the production figures, considered inter-annual variability in yield is recorded. For the prices, the average values have been taken as those perceived by the farmers, according to official statistics (CAPA, 2011).

To bring the models closer to the real conditions in the region, a number of restrictions have been taken into account, and have been introduced equally in both scenarios:

- Crop area: A total of 32 hectares are available on the farm.
- At maximum 30% of the available surface area can be subject to marginal management, concept already defined above.

- Given these are woody crops, and that the models under consideration are static and short-term, the maximum surface area of each species is limited to its present value (32% in olive, 8% in almond and 60% in vineyard). This restriction permits changes in variety within a species, changes in the type of irrigation, or for this to pass to marginal management.
- With respect to the availability of irrigation, due to the dryness of these regions, very strict conditions are introduced, fixing a use equivalent to the levels of habitual consumption, which according to the criteria of the experts consulted, can be maintained medium term (Table 1). Therefore, it is established that only 10% of the available surface area can receive some kind of irrigation, the water supplied cannot exceed 600 m^3 monthly for the whole farm, and that the total amount allotted to the farm is of 5,000 m^3 annually. The current price of irrigation water is 0.15 €/m^3.
- The other restrictions are derived from manual labour. The availability of family labour is fixed at an agricultural work unit (an AWU to be 2,160 hours a year), and hired labour is limited to complement what cannot be covered by family on a three-monthly basis.

The curves obtained will be consequence of the adaptation of the farm to increasing prices for irrigation water in the short term. The simulation models are applied to the manual scenario and to the mechanized scenario and are similar to those used to obtain the shadow prices, with the following considerations:

- The MAUT is obtained for the objectives: maximization of the net margin of the farm and minimization of total workforce.
- From the previously calculated margin (Table 1), the cost of the water (corresponding to the usual price, 0.15 €/m^3) is deducted and the value corresponding to each simulation, starting from 0 €/m^3, is added.
- The restrictions to the models, and the average volumes of irrigation applied to each variety of crop coincides with those previously described (Table 1).

The utility function characteristic of a representative farm of the region under study has been found, assuming that the farm owners will maintain their psychological attitude with regard to decision-taking for a short to medium term. A series of simulations are made with rising prices of irrigation water, in such a way that, each price is a new scenario in which utility is maximized, and from which we derive a cropping plan with a specific demand for irrigation water. Finally, the set of simulations carried out serves to set out the demand functions and will be a consequence of the adaptation of the farm short-term at increasing prices for irrigation water.

3.3 Results and discussion

Typically, the demand curves of the areas placed inland of the Mediterranean coastal, show large inelasticity; therefore farmers display a strong willingness to pay for each cubic meter of water. The question it should ask, then, is whether these high prices are affordable by Mediterranean farmers. For this reason, it has also obtained the maximum price of irrigation water that guarantees the family farm income.

Table 2 shows the achievement levels for each of the three objectives for the metrics L_1 and L_∞, the different cropping plans and the requirements of hired manual labour. The results

Species	Varieties, description	Irrigation	Annual water supply (m^3/ha)	Net margin manual-scenario (€/ha)	Net margin mechaniz.-scenario (€/ha)
Olive	Authochthonous: Grossal	Dry-land	0	315	314
Olive	Authochthonous: Grossal	Irrigated relief	700	662	734
Olive	Authochthonous: Grossal	Irrigated	1500	1314	1511
Olive	New: Arbequina	Dry-land	0	441	300
Olive	New: Arbequina	Irrigated relief	700	933	858
Olive	New: Arbequina	Irrigated	1500	1585	1611
Almond	Authochthonous: Comuna Group	Dry-land	0	236	330
Almond	Authochthonous: Comuna Group	Irrigated relief	700	151	329
Almond	New: var.Late-flowering	Dry-land	0	451	577
Almond	New: var.Late-flowering	Irrigated relief	700	360	568
Vineyard	Monastell in tube	Dry-land	0	550	564
Vineyard	Monastell in tube	Irrigated relief	1100	783	807
Vineyard	Monastell in tube	Irrigated	1900	1458	1492
Vineyard	Monastell in espalier	Dry-land	0	499	655
Vineyard	Monastell in espalier	Irrigated relief	1100	788	955
Vineyard	Monastell in espalier	Irrigated	1900	1409	1602

Source: own calculations

Table 1. Rainfed tree crops, decisional variables: description, net margin for scenarios and annual water supply

show a number of advantages on moving from the manual scenario to the mechanized scenario. With regard to the water requirements, in the most balanced cropping plan (L_∞), which is the one that demands most irrigation, it does not exceed 2,227 m^3/year on the whole farm in the manual scenario, and 2,418 m^3/year for the mechanized scenario. Given the strict conditions used to establish the models, it is possible to think that the proposed plans will be sustainable, even in these arid agricultural conditions. Moreover, in solution L_1 there are plans that do not necessitate irrigation, verifying the continuity of traditional dry-farming on its own.

Having reached this point, it is especially interesting to reflect on the behaviour of the profit maximization objective with respect to minimizing irrigation water. If the compromise sets are calculated just for these two objectives, these points can be represented on a Cartesian plane and, the slope of the line joining the points L_1 and L_∞, or trade-off, show us the opportunity cost or the shadow price of the irrigation water, understood in its marginal values. In other words, as the increase in the net margin of the farm if one applies an additional unit of water (Florencio-Cruz et al., 2002).

The lines obtained in both scenarios are represented in Figure 1. The volume of irrigation water required by such a plan is represented on the axis of abscissas, while the axis of ordinates shows the net margin this plan generates. The result is that, the shadow price of the water is 0.76 €/m^3 in the manual scenario and 0.87 €/m^3 in the mechanized ones. The highest shadow price obtained in both scenarios is very significant, and they are a useful orientation to the value of water in this dry-farming system. However, they have been obtained by exclusively evaluating the impact of irrigation water on the net margin of the farm; therefore, to obtain more rigorous information about how these crops would behave in the event of an increase in water prices, the demand curves will be calculated below.

	Manual scenario		Mechanized scenario	
Metrics:	L_1	L_∞	L_1	L_∞
Value of objectives:				
Net margin (euros)	10,950	14,889	12,520	16,241
Water (m^3)	0	2227	0	2418
Total manual labour (hours)	2,014	2,653	1,200	1,505
Optimisation activities (%):				
Olive. Grossal. Dry-land			2	13.3
Olive. Arbequina. Dry-land	32	27.4		
Olive. Arbequina. Irrigated		4.6		5
Almond. Var.Later flowering. Dry-land	8	8	8	8
Vineyard. Tube. Dry-land	30	42.7	60	60
Farm surface with marginal management	30	17.3	30	13.7
Total hectares properly cultivated (ha)	**22.4**	**26.5**	**22.4**	**27.6**
Net margin (euros per cultivated hectare)	**489**	**562**	**559**	**588**
Requirement annual of hired manual labour (hours)	**631**	**1052**	**0**	**106**

Table 2. Cropping plan and results for the three objectives analysed for compromise solutions in Spanish dry-lands. (Data for a family farm with an agricultural work unit and 32 hectares)

The demand curves obtained are shown in Figure 2. In the event of applying a hypothetical pricing policy, the way the farm behaves will vary according to its degree of mechanization, although we observe that water consumption in the lowest price range is equal in both scenarios. Such inflexible behaviour of the different price ranges should be highlighted, and undoubtedly the great shortage of this resource in these regions. The high productivity of water, even in small amounts, mean that the price the farm can pay for irrigation water can be increased.

In the manual scenario, there is a first range of maximum demand, between 0 and 0.51 €/m³; it continues with a drop to half the demand for tariffs of 0.52 to 0.55 €/m³ and ends up with cropping plans in completely dry-farming when the water costs over 0.56 €/m³. In the mechanized scenario the demand is constantly at maximum until it reaches 0.91 €/m³, at which point the chosen cropping plan changes to one that is strictly dry-farming. The different response must be looked at in the different degree of mechanization. Technology improves management and enables farms to face more effectively the greater labour requirements that arise from irrigated crops. This limitation is accentuated if the labour (especially harvesting) is carried out manually, and for this reason the mechanized farms are better able to pay higher water prices.

The price of water has repercussions on the cropping plan resulting from each simulation. When the prices are low, water is demanded for irrigation and this is destined solely to the olive, specifically to the olive Arbequina irrigated, but for both the almond and the vineyard dry-farming is always chosen. In the manual scenario the dry farmed olive is the Arbequina, while in the mechanized scenario is the autochthonous variety Grossal. With respect to the vineyard, in the manual scenario it is trained in tube, while in the mechanized it is trained in espalier (which is more productive but requires a greater initial investment). The almond chosen is a late-flowering variety in both scenarios. The cropping plans in the mechanized scenario are more economically viable, which means that, with prices of over 0.51 €/m³, they can demand greater quantities of water than in the manual one.

The main conclusions are:

- The different sections of the demand curves demonstrate very inflexible behaviour, which is justified by the fact that the olive, vineyard and almond are woody species that use small amounts of irrigation water very effectively.
- The effect of the price of water on the farm's income make a higher degree of mechanization necessary in order to face high irrigation-water prices. The current price of water is 0.15 €/m³, and although it could increase, to ensure a minimum income for the farm of 21,500 € annually, water cannot exceed more than 0.24 €/m³ in a manually worked farm, or more than 0.44 €/m³ if it is mechanized.
- To increase mechanization may be the most straightforward strategy to ensure the survival of the farms in the Spanish dry-lands, short to medium term, and likewise strengthen their sustainability. As all the results have been obtained considering the operations that demand the most expensive machinery to be hired, it can be deduced that it is a strategy that can be assumed by all the farms. Thus, it will be essential to increase the degree of mechanization in order to guarantee the viability of this agriculture if the current trend of increasing irrigation-water prices is consolidated.

4. Case 2: Irrigated woody crops (table-grapes): Response to variations in irrigation water pricing

4.1 The most outstanding traits of the table-grape regions

Spain, with 15.2% of the vine-planted surface area in the world, is the leader in terms of the extension this crop covers. Although only 5% of this production is destined to fresh-fruit consumption, cultivation of the table-grape (*Vitis vinifera* L.) is important given its long tradition. Spain is the fifth table-grape producer world-wide in the northern hemisphere,

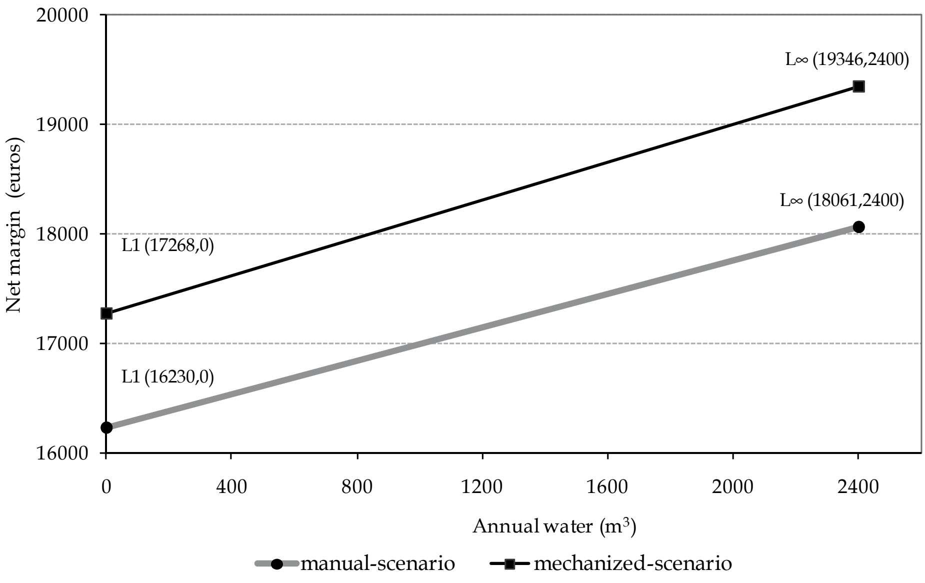


Fig. 1. Shadow price of irrigation water for two scenarios in Spanish dry-lands (Data for family farm with 1 AWH and 32 hectares)

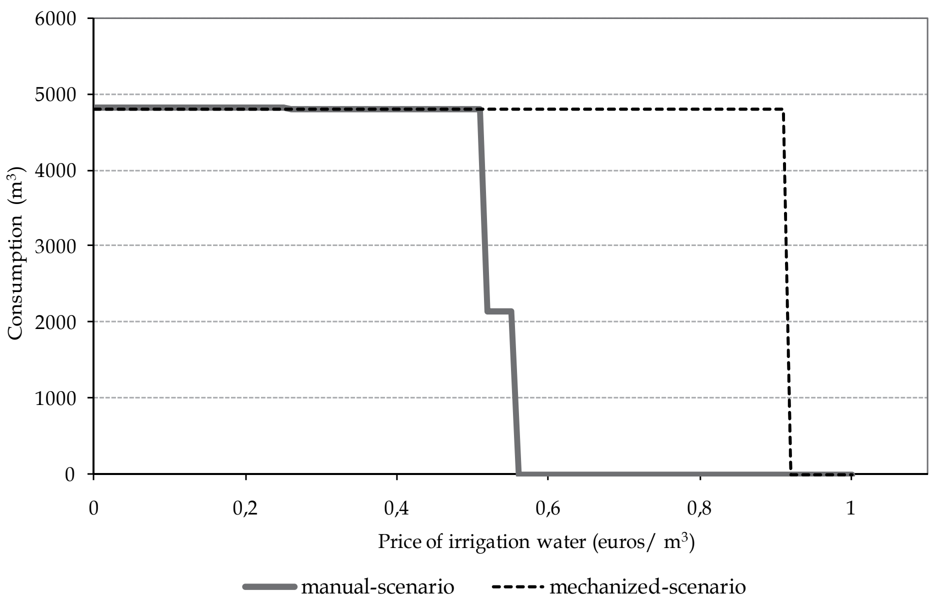


Fig. 2. Demand functions for irrigation water for the two scenarios in Spanish dry-lands

and the second in Europe, surpassed only by Italy. It is the sixth exporter in the world, coming after Chile, Italy, USA, South Africa and Mexico. In 2009, Spain exported 117,143 Tn of fresh grapes, of which 99% were destined to European countries. Table grape is a very typical Mediterranean crop, accounting for 79.3% of the area and 88.8% of the production between the Regions of Murcia and the Valencian Community (MARM, 2011). Both these regions are situated next to the Mediterranean, have a warm climate, but are greatly lacking in rainfall, with average precipitation of below 300 mm annually. Water is the scarcest and most valuable natural resource, given the over-exploitation of aquifers or its low quality, and is the main reason why this crop is partially abandoned. The temporal marginal management are common in table-grape, that is to say, they are left to basic care for a certain amount of time, which habitually consist of maintenance pruning and minimum tillage. If the circumstances that have favoured this situation (scarcity of irrigation water, lack of personal and economic incentive of the agricultural producers, etc.) are longer lasting, then this abandonment becomes definitive. Rejecting optimum crop management is a common practice in these regions of production, and faced with the lack of irrigation water, the choice is to destine the one available to the most economically viable plots.

4.2 Information and methodology

The Spanish table-grape farms are very small in size, 72% of those in Alicante (Valencian Community) and 66% of those in Murcia are smaller than 5 ha (INE, 2011). In this study, a 5 ha family farm has been used as reference. The two cropped areas are *Valle del Vinalopó* (Alicante) and *Valle del Guadalentín* (Murcia), geographically closed but technically and managerially different.

Thus, in the *Valle del Vinalopó* there are 9,500 ha of grape (MARM, 2011), forming a well-defined agrarian system that has remained very stable over time. Its most defining feature is its “bagging”, by which the bunches of grapes are covered by a paper bag, from just before veraison up until harvesting. Technology is found at an acceptable level, but it is possible to improve the mechanization of the labour. The varietal composition has undergone scarce variation over time, and is fundamentally based on the Italia and Aledo varieties, although important changes are foreseeable in the coming years, and seedless varieties will be introduced, which are still in minor representation. The situation is different in the Region of Murcia, where the surface area dedicated to grape has increased in recent years, reaching 5,159 hectares in 2010 (CARM, 2011) and where new production zones have appeared, with large business producers and a strong bid for seedless varieties. In general terms one can also talk about family farms, but the important investment in capital and technology mean that noticeable differences exist between Murcia and Alicante. There is intense activity concerning the introduction of new plant material, the traditional varieties like Italia and Ohanes have diminished, and instead there has been an increase in the surface area planted with Dominga, Napoleon and, above all, the seedless or early varieties (Superior, Crimson and Red Globe for example).

Currently, in both regions, the growing operation being perfected concerns particularly irrigation, which is bringing about massive implementation of drip irrigation. This type of irrigation covers 50% of the surface area at present, and it is foreseeable that it will reach

90% soon. The shortage of irrigation water in these zones, the irregularity of the supplies and the deficiencies in the quality also encourage the grape-growers to construct accumulation reservoirs, which is more widespread in the Murcia region.

Therefore, the technological improvements that are being adopted more quickly in Spanish table-grape cultivation are: an increase in the average power of the machinery to carry out the labour and the phyto-sanitary treatments, use of tying machines for the summer pruning, use of pre-pruners (in espaliers), generalized use of shredders for the pruning remains and substitution of the traditional irrigation systems for programmed drip irrigation. Moreover, they are improvements that are beginning to spread to the new staking structures (higher espalier in Y in Alicante), and the use of mesh or plastic covering, which are common in Murcia (Fernández-Zamudio et al., 2008).

Maximizing profits (equation 8) is the primary objective of Spanish grape growers, but given the strict water conditions of the regions studied, they must also minimize consumption of irrigation water (equation 9) The decisional variables will be the surface areas occupied by the different growing activities. Table 3 describes the modelized variables, together with their annual water allotment and the net margins in the two technological scenarios analyzed. Scenario-1 represents the traditional production conditions for table-grape in the two zones. From these, one moves to another productive context, in which a series of technological improvements have been adopted, towards a scenario where the two zones would appear to be moving towards according to regional agricultural technicians (scenario-2). The restrictions of the models are a maximum monthly and yearly irrigation allotments, maximum area of cultivation that will be subject to adoption of drip irrigation, change to Y trellises and covering with net screening, as well as those restrictions derived from the market (new varieties introduction).

For analyzing the two objectives together and obtain water shadow prices, compromise programming has been used, while to obtain the demand curves a lineal mathematical programming has been applied, being the objective:

$$Max \sum_{i=1}^{n} NM_i \cdot X_i - Q_i \cdot X_i \cdot p_q \tag{11}$$

Where NM_i is the net margin of the activity i, X_i is the cultivated area, Q_i its yearly quota of irrigation water. Also, p_q is the price of irrigation water for each parameter (from zero to 4 Euros per cubic meter). This is the real price that the grower pays for each cubic meter of water; this price includes administrative costs of delivery, maintenance of the infrastructure, energy for pumping, and other taxes or charges. The restrictions of the model are the same as in compromise programming.

4.3 Results and discussion

From the optimal cropping plans obtained (Table 4), it is possible to deduce that technological improvements will broaden economic expectations of grape growers. Net profits will increase by a mean of 15% in Alicante and 97% in Murcia, figures that concord with technological changes introduced in each region.

(1)	Variable description	Irri-gation type	Sce-nario	Q_i (m^3/ha) (2)	Net Margin (3) Scen.-1 (€/ha)	Net Margin (3) Scen.-2 (€/ha)
A	Aledo.Traditional espalier. Bagged	Flood	1& 2	3900	7311	7430
A	Aledo. Traditional espalier. Bagged	Drip	1& 2	4000	8156	8015
A	Aledo. Y espalier. Bagged	Drip	1& 2	4000	8999	8836
A	Italia. Traditional espalier. Bagged	Flood	1& 2	3900	5000	4917
A	Italia. Traditional espalier. No bagged	Flood	1& 2	3900	5233	5150
A	Italia. Traditional espalier. Bagged	Drip	1& 2	4000	4916	4872
A	Italia. Traditional espalier. No Bagged	Drip	1& 2	4000	5638	5582
A	Italia. Trellis. Bagged	Flood	1& 2	3900	5199	5247
A	Italia. Trellis. Bagged	Drip	1& 2	4000	6160	6223
A	Italia. Y espalier. Bagged.	Drip	1& 2	4000	5934	5771
A	Victoria. Y espalier. No bagged	Drip	2	3500		7931
A	Superior. Y espalier. No bagged	Drip	2	3500		10866
A	Marginal management		1& 2	0	-720	-720
M	Napoleon. Wood trellis	Flood	1& 2	5100	4433	4509
M	Superior. Wood trellis	Flood	1& 2	5100	7224	7014
M	Italia. Wood trellis	Flood	1& 2	5100	3675	3679
M	Dominga. Wood trellis	Flood	1& 2	5100	6995	6959
M	Red Globe. Wood trellis	Drip	1	4620	7112	
M	Superior. Wood trellis	Drip	1	3990	8754	
M	Superior. Galvan.-iron trellis	Drip	2	3990		7939
M	Red Globe. Galvan.-iron trellis. Mesh cover	Drip	2	4620		6163
M	Superior. Galvan.-iron trellis. Mesh cover	Drip	2	3990		13573
M	Superior. Galvan.-iron trellis. Mesh & plastic	Drip	2	4550		15635
M	Crimson. Galvan. -iron-trellis. Mesh cover	Drip	2	4860		17590
M	Marginal management		1& 2	0	-787	-787

(1) Areas: Alicante (A), Murcia (M). (2) Qi is annual water supply for i activity. (3) Net margins excluding manual labour cost. Source: Own elaboration

Table 3. Decisional variables of Spanish table-grape: description, net margin for scenarios and annual water supply

Water shadow prices are higher in Alicante, where smaller water allocations than in Murcia are allowed, and water is an even more valuable resource; thus, productivity of each cubic meter is higher even when technology is adopted. In any case, the resulting values are very high and caution is recommended when considering them. To determine what the real affordable price is, demand functions were calculated in such a way that the cost of the required water is subtracted from each resulting cropping plan. The cost of water is concordant with the price included in each parameterization. The results of this calculation are Figure 3, where it is observed that the production units in Murcia demand more water than those of Alicante, up to 0.60 €/m³, a price at which Murcia would begin to reduce consumption. The curves of scenario-2 show a higher demand than those of scenario-1 since, if the grower has technology, other limitations, such as labour, can be compensated, and more productive varieties will be planted, but these consume more water.

Since the demand for water only begins to decrease when prices are very high, availability of the resource is an even greater limitation than its price. Analyzing the repercussion of the price of water on net profit (Figure 4), it can be observed that with prices above 1.5 €/m³ only a very low profit is obtained, or there may even be losses. If a reference income is set at 18,000 euros to compensate the yearly work of the entrepreneur, the maximum price that small grape growers in Alicante can afford is 0.25 €/m³ in scenario-1 and 0.60 €/m³ in scenario-2. In Murcia, this reference income is achieved when prices are lower than 0.15 Euros per cubic meter in scenario-1, while the current price of water is 0.18 €/m³, meaning that only those growers with more technology are achieving profits. In the case of implementing the improvements of scenario-2, in Murcia it is possible to surpass the reference income when the price of water is not more than 1.1 €/m³.

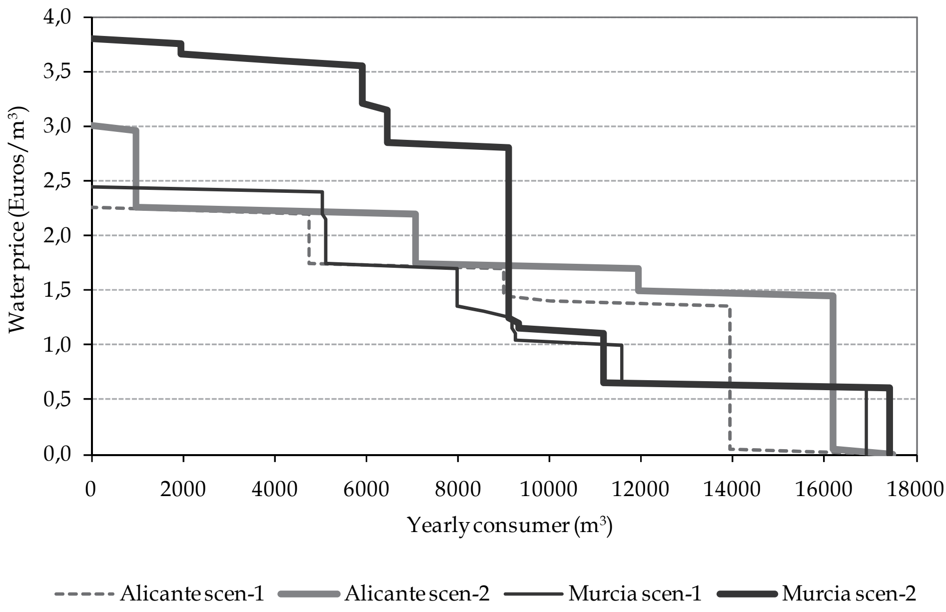


Fig. 3. Irrigation water demand curves in Spanish grape-table (Data for 5 ha production unit)

The main conclusions are:

- To guarantee the continuity of the Spanish table-grape farms (most of them being small and family-run), the adoption of technological improvements seems to be essential. An essential improvement (being massively applied in both areas) is the increase of surfaces with drip-irrigation. This technique enables choice of the watering times for the plots, achieving an optimization of the allotments awarded in the plantation, these usually being lower than the theoretical needs of the crops.

- The scarce response of the demand, because of rising water prices, and therefore, of implementation of a pricing policy, denotes that the problem of these producing regions is its availability rather than its price. This conclusion is only valid if the growers have an acceptable profitability, which cannot be assured in the medium or long-term with the current market situation. To achieve the minimum profit fixed in this study, the price of water should not exceed 0.15 €/m³ in Murcia and 0.25 €/m³ in Alicante. These prices could be considerably higher if growers improve their level of technology. Therefore, the adoption of technology will be the most direct strategy for increasing expectations of continuing production of the growers, who, in general, do not feel capable of overcoming the iron rules of the markets.

Proportion of activities (in %)[1]	**Irrigation Type**	**Scenario-1**		**Scenario-2**	
		L_1	**L_∞**	**L_1**	**L_∞**
ALICANTE (VINALOPO):					
Aledo. Traditional espalier. Bagged	Flood			16.8	
Aledo. Traditional espalier. Bagged	Drip	40.5	40.5	23.7	40.5
Aledo. Y espalier. Bagged	Drip	4.5	4.5	4.5	4.5
Italia. Traditional espalier. No bagged	Flood	20.3	20.2		
Italia. Traditional espalier. No Bagged	Drip	4.7	4.8	10	12.5
Victoria. Y espalier. No bagged	Drip			10*	10*
Superior. Y espalier. No bagged	Drip			5*	5*
Proportion with marginal management		30*	30*	30*	27.5
Total Net Margin (€)		**21,175**	**21,177**	**23,785**	**24,874**
Total manual labour (h)		**1,345**	**1,345**	**1,210**	**1,254**
Total water consumption (m³)		**13,898.5**	**13,899**	**13,841**	**14,428**
Shadow irrigation prices (€/m³)		**4**		**1,9**	
MURCIA :					
Napoleón. Wood trellis	Flood	25	27	5	5
Dominga. Wood trellis	Flood	5	5	10	10
Superior. Wood trellis	Flood	10	8		
Superior. Wood trellis	Drip	30	32		
Superior. Galvan. iron trellis. Mesh cover	Drip			45*	45*
Crimson. Galvan. iron trellis. Mesh cover	Drip			10*	10*
Proportion with marginal management		30*	28	30*	30*
Total Net Margin (€)		**17,511**	**18,034**	**35,070**	**35,103**
Total manual labour (h)		**1,835**	**1,873**	**2,154**	**2,158**
Total water consumption (m³)		**16,185**	**16,607**	**15,233**	**15,285**
Shadow irrigation prices (€/m³)		**1,24**		**0,63**	

1) Respect total surface (5 ha). * Limit coincident with the restrictions of the models.
Source: Own calculation

Table 4. Cropping plan and results for two scenarios in Spanish table-grape

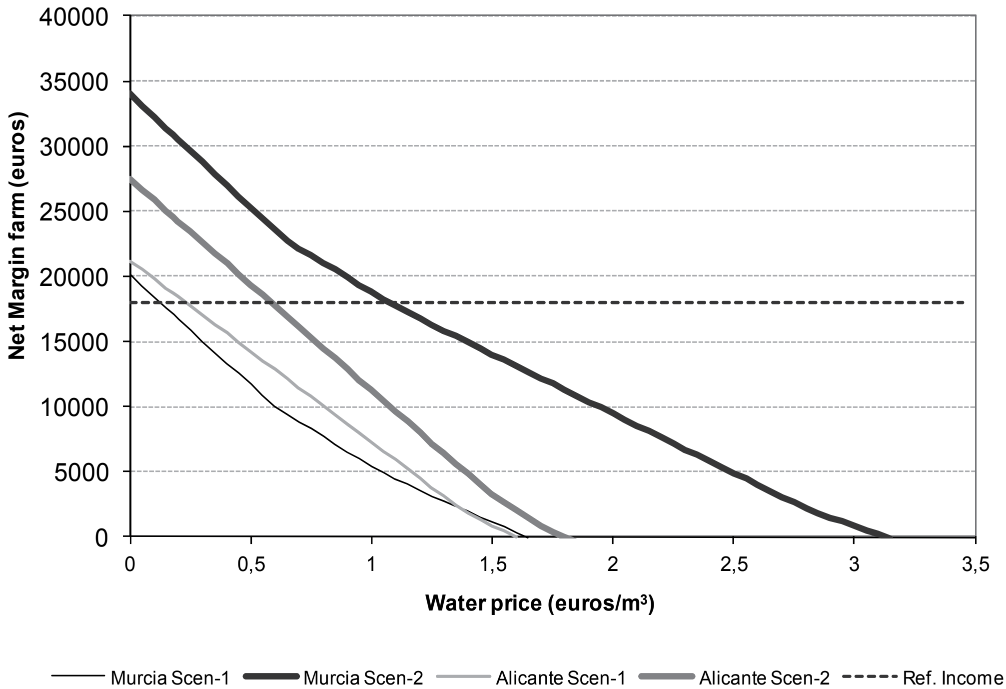


Fig. 4. Repercussion of the price of water on net profit in Spanish grape-table (Data for 5 ha production unit)

5. Conclusion

Water demand curves have been used to analyze the trends of the most important Mediterranean woody crops when up against tariff policies that differ from the current ones. These calculations have been applied to olives, almonds and vineyards grown in the inland regions of the Valencian Community, and table grapes in the two main production areas in the southeast Spanish Mediterranean region. The main conclusions derived from the two case studies are:

- The shadow price of water is very high for all crops under study, increasing in those scenarios with a low technological level. Technology can offset other agronomic technical limitations of the farm-holding, optimizing the production process, and therefore the shadow price of water is reduced. Usually farmers believe that technology is their best strategy to improve farm viability, although, on the other hand, technological improvements allow more productive varieties to be grown, which typically require more water, and as a result the more technologically developed scenarios are also more demanding of water resources.
- Irrigated crops with moderate irrigation requirements, such as table grapes, show highly inelastic demand curves, at least in the first price phases. As this resource becomes more expensive, demand falls while the surface area with marginal management increases, which may be the step prior to future crop abandonment. For the typical rainfed crops, the demand curves display strong inelasticity, demonstrating the huge value of having an extra cubic meter of water, this to be applied at specific

moments and in low doses. In general, Mediterranean crops make very efficient use of the water supplied, even at doses below agronomic irrigation needs. Allocations should be supplied at the point in time most crucial to the crop, which often coincides with reduced water availability on the farm, and in this moment availability becomes a more limiting factor than the price. This does not mean water high prices can be paid, since the real affordable price is much lower.

- Water prices to be paid can theoretically be very high, as with respect to woody species their survival depends on timely supply, which does not indicate that sustained high prices are to be met. In fact, the first step taken by farmers is to increase the surface area with marginal management (prior step to abandonment) and concentrate investment in the more profitable fields or varieties. Therefore, it is foreseeable that a tariff policy implementing high prices would result in the gradual abandonment of Mediterranean crop cultivation and thereby reduce the economic activity in large tracts of land, especially in the inland regions.

Further research based on woody crops in areas where these are implemented would be desirable for the achievement of a sustainable and efficient use of water. The effects of a water pricing policy in other highly extended woody Mediterranean crops, such as citrus, almond, pomegranate or peach, is still unknown. This research would inform farmers and policy makers about reliability of water pricing policies in this kind of crops, avoiding undesirable effects on farmers and environment, and enforcing the reliability of the measures proposed by the WFD.

6. Acknowledgment

We are grateful to the financial aid received from the Spanish Ministry of Science and Innovation and the ERDF through the GEAMED project "*Gestión y eficiencia del Uso Sostenible del agua de Riego en la Cuenca mediterránea*" (AGL2010-22221-C02-01). Thanks to Dr. Pedro Caballero, for his comments on an earlier draft of this chapter.

7. References

Amador, F., Sumpsi, J.M. & Romero, C. (1998) A non-interactive methodology to assess the farmers' utility function: An application to large farms in Andalusia. Spain. *European Review of Agricultural Economics,* Vol. 25, pp. 95-109. ISSN: 1464-3618

Bazzani, G.M., Di-Pasquale, S., Gallerani, V. & Viaggi, D. (2004). Irrigated agriculture in Italy and water regulation under the European Union water framework directive. *Water Resource Research*, Vol. 40(7), W07S04. ISSN 0043-1397

Ballestero, E. & Romero, C. (1991). A theorem connecting utility function optimization and compromise programming. *Operational Research Letter,* Vol. 10, pp. 412-427. ISSN: 0167-6377

Ballestero, E., Alarcón, S. & García-Bernabeu, A. (2002). Establishing politically feasible water markets: a multi-criteria approach. *Journal of Environmental Management,* Vol. 65(4), pp. 411-429. ISSN: 0301-4797

Berbel, J. & Gómez-Limón, J.A. (2000). The impact of water-pricing policy in Spain: an analysis of three irrigated areas. *Agricultural Water Management,* Vol. 43, pp. 219-238. ISSN: 0378-3774

Berbel, J., Mesa-Jurado, M.A. & Pistón, J.M. (2011). Value of irrigation water in Guadalquivir Basin (Spain) by the Residual Value Method. *Water Resources Management,* Vol. 25, pp. 1565-1579. ISSN: 0920-4741

CAPA (Conselleria de Agricultura, Pesca y Alimentación, Generalitat Valenciana). (March 2011). Publicaciones. Informes del Sector Agrario y Boletines de Información Agraria. Available from http://www.agricultura.gva.es/web/web/guest/la-conselleria/publicaciones/boletin-de-informacion-agraria.

CARM (Comunidad Autónoma de la Región de Murcia). (March 2011). Estadística agraria regional. Superficie regionales. Series históricas regionales. Available from http://www.carm.es/web/pagina?IDCONTENIDO=1391&IDTIPO=100&RASTRO=c488$m1174,1390

Dyer, J.S. (1977). *On the relationship between goal programming and multiattribute utility theory*. Discussion paper 69. Ed. Management Study Center. University of California.

Easter, K.W. and Liu, Y. (2005). Cost Recovery and Water Pricing for Irrigation and Drainage Projects. World Bank Technical Paper, Washington, D.C., 55p.

Edwards, W. (1977). Use of multiattribute utility measurement for social decision making. In: *Conflicting objetives in decision* (Bell D.E.; Keeney R.L. & Raiffa H., Ed.). John Wiley & Sons, New York. pp. 247-276

Fernández-Zamudio, M.A. & De-Miguel, M.D. (2006). Sustainable management for woody crops in Mediterranean dry-lands. *Spanish Journal of Agricultural Research*, Vol. 4(2), pp. 111-123. ISSN: 1695-971-X

Fernández-Zamudio, M.A., Alcón, F. & De-Miguel, M.D. (2007). Irrigation water pricing policy and its effects on sustainability of table grape production in Spain. *Agrociencia*, Vol. 41(7), pp. 805-845. ISSN: 1405-3195

Fernández-Zamudio, M.A., Alcón, F. & Caballero, P. (2008). Economic sustainability of the Spanish table grape in different water and technological contexts. *New Medit*, Vol. VII, num. 4, pp. 29-35. ISSN: 1594-5685

Florencio-Cruz, V., Valdivia-Alcalá, R. & Scott, C.A. (2002). Water productivity in the alto río Lerma (011) irrigation district. *Agrociencia*, Vol. 36, pp. 483-493. ISSN: 1405-3195

Gómez-Limón, J.A. & Berbel, J. (2000) Multi Criteria Analysis of Derived Water Demand Functions: a Spanish Case Study. *Agricultural Systems*, Vol. 63, pp. 49-72. ISSN: 0308-521X

Gómez-Limón, J.A., Arriaza, M. & Berbel, J. (2002). Conflicting implementation of agricultural and water policies in irrigated areas in the EU. *Journal of Agricultural Economics*, Vol. 53(2), pp. 259-281. DOI: 10.1111/j.1477-9552.2011.00294.x

Gómez-Limón, J.A., Riesgo, L. & Arriaza, M. (2004). Multi-criteria analysis of input use in agriculture. *Journal of Agricultural Economics*, Vol. 55(3), pp. 541-564. DOI: 10.1111/j.1477-9552.2004.tb00114.x

Gómez-Limón, J.A. & Riesgo, L. (2004a). Water pricing: Analysis of differential impacts on heterogeneous farmers. *Water Resources Research*, Vol. 40, W07S05. ISSN 0043-1397

Gómez-Limón, J.A. & Riesgo, L. (2004b). Irrigation water pricing: differential impacts on irrigated farms. *Agricultural Economics*, Vol. 31(1), pp. 47-66. ISSN: 1574-0862

Gurovich, L.A. (2002). Irrigation scheduling of table grapes under drip irrigation: an approach for saving irrigation water and energy cost in Chile. *International Water Irrigation*, Vol. 22(2), pp. 44-50.

Huirne, R.B.M. & Hardaker, J.B. (1998). A multi-attribute model to optimise sow replacement decisions. *European Review of Agricultural Economics,* Vol. 25, pp. 488-205. ISSN: 1464-3618

Hearne, R.R. & Easter, K.W. (1997). The economic and financial gains from water markets in Chile. *Agricultural Economics*, Vol. 15(3), pp. 187-199. ISSN: 1574-0862

INE (Instituto Nacional de Estadística). (March, 2011). Estadísticas agrarias. Encuesta sobre la estructura de las explotaciones agrícolas. Available from http://www.ine.es/inebase/menu6_agr.htm

Jorge, R.F., Costa-Freitas, M.B., Seabra; M.L. & Ventura, M.R. (2003). Droughts: will farmers change therir decisions?. *New Medit*, Vol. 2(4), pp. 46-50. ISSN: 1594-5685

Keeney, R.L. & Raiffa, H. (1976). *Decisions with multiple objectives: preferences and value trade offs*. John Wiley & Sons, New York.

MARM (Ministry of Agriculture, Fisheries and Food of Spain). (March, 2011). Anuario de estadística. Available from http://www.marm.es/es/estadistica/temas/anuario-de-estadistica/default.aspx

Mesa-Jurado, M.A., Berbel, J. & Orgaz, F. (2010). Estimating marginal value of water for irrigated olive grove with the production function method. *Spanish Journal of Agricultural Research*, Vol. 8, special issue (S2), pp. 197-206. ISSN: 1695-971-X

Romero, C. & Rehman, T. (2003). *Multiple criteria analysis for agriculture decision*. Elsevier, Amsterdam. ISBN 0444503439

Sabuni, M. & Bakshoudeh, M. (2004). Determining the relationship between the opportunity cost of water and farmers'risk attitudes, using multi-objective programming. *Agr Sci Tec,* 18(1), pp. 39-47.

Sumpsi, J.M., Amador, F. & Romero, C. (1996). On farmer's objectives: A multi-criteria approach. *European Journal of Operational Research,* Vol. 96, pp. 64-71. ISSN: 0377-2217

Sumpsi, J.M., Garrido, A., Blanco, M., Varela, C. & Iglesias, E. (1998). *Economía y Política de Gestión del Agua en la Agricultura. Ministerio de Agricultura, Pesca y Alimentación*, Ed. Mundi Prensa, 84-7114-781-5, Madrid, Spain.

Varela-Ortega, C., Sumpsi, J. M., Garrido, A., Blanco, M. & Iglesias, E. (1998). Water pricing policies, public decision-making and farmers response: Implications for water policy. *Agricultural Economics*, Vol. 19, pp. 193– 202. ISSN: 1574-0862

Yu, P.L. (1973). A class of solutions for groups decision problems. *Management Science,* Vol. 19, pp. 936-946. DOI: 10.1287/mnsc.19.8.936

Zeleny, M. (1973). *Compromise programming. Multiple criteria decision making*. (Zeleny M., and Cochrane J., Ed.). University of South Carolina Press, Columbia SC. pp.262-301.

6

Irrigation Institutions of Bangladesh: Some Lessons

Nasima Tanveer Chowdhury
Environmental Economics Unit (EEU)
Department of Economics
Gothenburg University, Gothenburg
Sweden

1. Introduction

The objective of this chapter is to highlight some issues of existing irrigation institutions and their impact on cost and price of irrigation water in Bangladesh agriculture. Water is scarce in winter and agriculture is the major water using sector for irrigation in Bangladesh. The study mainly deals with how public institutions and water markets have evolved over time in response to changes in irrigation technology and how they affect the cost and price of irrigation water. There are many government run irrigation projects in the Northwest region (NW) of Bangladesh. Recently Bangladesh Water Development Board (BWDB) has handed over these irrigation projects to water user groups (mainly medium and large farmers) for management and cost recovery.

At present there are 5 types of irrigation systems which have given rise to different institutional setups. These institutions play a crucial role in water pricing. Both government and the private sector have been practising various methods over time for water allocation to the farmers' fields. The objective of this study is to examine how these institutions have come into existence as they are responsible for shaping water prices both in the public and private sector. Currently the public sector is responsible for maintaining the surface water irrigation projects which is only 10 percent of the total irrigation. The rest is the private sector mainly groundwater irrigation using minor irrigation devices. In the NW region irrigation is almost entirely dependent on groundwater due to scarcity of surface water. In December 2007 I had a focussed group discussion in the NW region of Bangladesh and use the results to understand how irrigation institutions are working in the region and how it affects irrigation cost and volumetric price per unit of water. Farmers in Bangladesh do not pay per m^3/litre for irrigation water; they pay for pumping cost if any and labour charges when required.

Bangladesh is an agricultural country divided into 7 hydrological regions. The average annual rainfall varies from 1,200 mm in the extreme west to over 5,000 mm in the northeast (WB, 2000). About 80 percent of the total rainfall occurs during the monsoon from June to September. In the post-monsoon (October -November) and winter period (December - February) only 10 percent of the annual rainfall is available (WB, 2000). Rainfall is extremely unreliable in the subsequent pre-monsoon period (March - May). On an average there is about 10 percent of the annual rainfall in this period (WB, 2000). On the whole there is a seasonal lack of water depending on the presence and the duration of the monsoon. Water is very scarce in the south and northwest region of Bangladesh during the winter.

Being a country of 140 million inhabitants, agriculture is still the major water using sector for surface and groundwater irrigation with rice cultivation, the single most important activity in the economy. In winter more than 70 percent of crop production is *boro* rice. *Boro* rice is a major food crop which uses up a lot of water per hectare (ha) in the production process. According to one estimate of Biswas and Mondol (1993) it is 11, 500 m^3 per ha. Demand for both surface and groundwater for irrigation is on the rise in the dry season which is 58.6 percent of the total demand for water (Chowdhury, 2008) in order to feed a growing population where at least 40 million people do not have a square meal.

Between 1944 and 1999 BWDB spent more than US$1700 m on flood control drainage irrigation (FCDI) projects (WB, 2006). Recently BWDB has handed over these projects to water user groups (mainly medium and large farmers) on the basis of average pricing. This gives rise to a conflict of interests between very small, small farmers and the WUG and hence it is not functional as it should be. More over water has many other uses in the society, fisheries, navigation, mangrove forests, river morphology and not to mention household and industrial uses. Therefore during the dry season water has a high opportunity cost due to competition from all the uses in addition to upstream intervention. It is imperative that farmers pay the true opportunity costs of irrigation water from the perspective of sustainable water use.

International Rice Research Institute (IRRI) conducted an Agricultural Household Survey in Bangladesh in 2000, 2004 and 2008 for 3 crop seasons and collected data on costs of inputs (including irrigation water) and returns on investment from a nationally representative sample of 1880 farm households from 62 villages belonging to 57 of 64 districts of Bangladesh. But the data do not have any information on the volume of irrigation water used in the fields or price per unit. Irrigation is the total irrigation costs measured in BDT (Bangladesh Taka) and we do not know the price per unit of water or the number of hours the pump is used for pumping water. The data available are for total cost of irrigation per household. The costs of irrigation are basically the costs of pumping water. Farmers mainly use low lift pumps for pumping water from surface water sources and shallow and deep tube wells from aquifers and groundwater. I conducted a focussed group discussion in the Northwest region to validate the IRRI data findings about irrigation costs and gather some information about the per unit water costs/prices they bear/pay for using different types of irrigation. Focussed group discussion is useful in case of small samples as opposed to other methods for gathering information within a short time.

2. Irrigation institutions

The 5 types of irrigation systems are traditional or local method, canal irrigation project of the government, low lift pump, shallow and deep tube well. When surface water was abundant farmers solely depended on rivers, canals and ponds to irrigate their fields with traditional local methods where the maintenance cost of the apparatus and labour charges when required constituted the costs of irrigation. With the growing population and the introduction of high yielding varieties of rice the government built huge surface water irrigation projects to take care of dry season irrigation. The cost of irrigation became the maintenance of the field channels from the tertiary outlets to the farmers' fields. With the scarcity of surface water in the rivers and canals and advent of groundwater irrigation farmers started paying for pumping water which consists of maintenance of the pumps, fuel cost (electricity or diesel) and the salary of the pump mechanic if required. Farmers use low lift pump to pump water from surface water sources and shallow or deep tube wells for groundwater which are known as minor irrigation devices. The use of low lift pump is limited by the availability of surface water in the canals and rivers during the dry season. Most deep tube wells are government owned and maintained by the public authority. The rest are run on a cooperative or joint ownership. Since investment in deep tube well is lumpy in nature farmers prefer shallow tube wells. Therefore the public sector irrigation institutions are the ones that are taking care of canal irrigation projects of the government and will be discussed in section 2.1. The private sector is the groundwater irrigation using minor irrigation devices to be dealt with in section 2.2.

2.1 Public sector

In Bangladesh irrigation is mainly for *boro* rice production in addition to wheat and some other winter crops. Since the 1950s more than 600 water resources schemes have been completed (WB, 2006). These projects ranged from single structure schemes with an impacted area of less than 1,000 ha to large scale multipurpose schemes potentially impacting as much as 100,000 ha. Most were designed to provide flood control, drainage, irrigation or some combination of these. In the late 1950s the government emphasised large scale surface water development projects. Some of the biggest surface irrigation projects are GK (Ganges-Kabodak) project, Pabna Irrigation project, Meghna-Dhonogoda project, Chandpur Irrigation Project, Karnaphuli project, Kaptai project, DND project, Narayanganj-Narshingdi Project, Teesta Project etc. In the mid 80s there was a major breakthrough in HYV (high yielding varieties) rice cultivation through the innovation of Bangladesh Agricultural Research Institute (BARI) and Bangladesh Rice Research Institute (BRRI) and which was possible due to large surface water irrigation projects.

These systems are being run by public agencies like BWDB, Bangladesh Rural Development Board (BRDB) etc. at the district and Upazila level. BWDB is the major public sector agency under the Ministry of Water Resources responsible for planning and execution of over 400 projects developing flood control, drainage and surface water irrigation projects. It also shares an interest in groundwater irrigation as well as in minor surface irrigation with BRDB, Bangladesh Agriculture Development Corporation (BADC) and Local Government Engineering Department (LGED). Earlier, this organization was pioneer in tapping ground water for irrigation in the northern Bangladesh; but subsequently its role in groundwater development was overtaken by BADC and later on by private sector. Major investments in the water sector are made by the Ministry of Water through BWDB and by the Ministry of Local Government and Rural Development through its LGED.

Participatory water management

In 1994 the Ministry of Water Resources formulated guidelines for people's participation in water development projects to involve local people in water resource projects with the help of officials and experts from BWDB, LGED, Water Resources Planning Organisation (WARPO), BADC, Department of Agricultural Extension (DAE), Department of Environment (DOE), Department of Forestry (DOF) and the Department of Livestock (DOL).

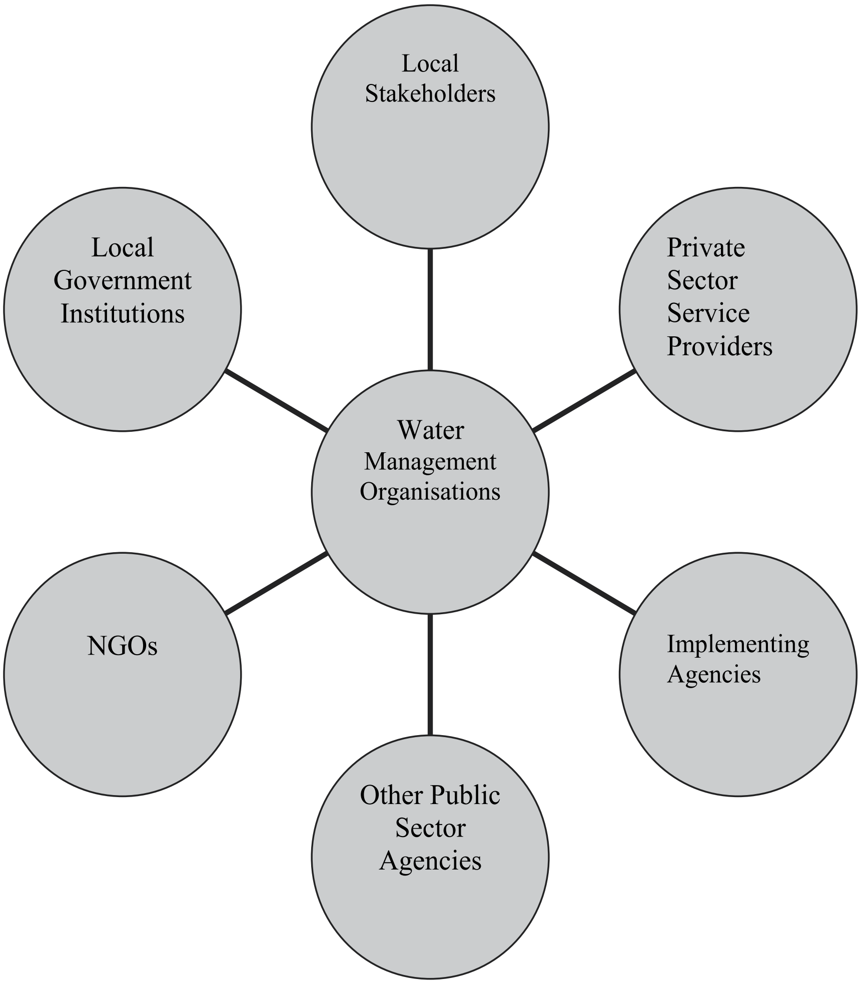


Fig. 1. Stakeholders of Participatory Water Management

Source: Ministry of Water Resources, GOB (2001)

Implementing Agencies are BADC, BWDB, LGED, Barind Multipurpose Development Authority (BMDA) and DOF. Other public sector agencies include DAE, BRDB, Forest Department (FD), DOE, BIWTA, Bangladesh Inland Water Transport Corporation (BIWTC), Department of Cooperatives (DOC), Department of Livestock Services (DLS), Ministry of Land (MOL) and Ministry of Women and Children Affairs (MWCA).

The principle that community resources must be managed by the community concerned along with local government institutions guides participatory water management. The National Water Policy emphasises the issue of participatory water management through planning, stakeholder participation, public and private management, economic and financial management and institutional policy. Local Governments (Parishads) are the principal agencies for coordinating the design, planning, implementation, and operation and maintenance (O&M) of publicly funded surface water resources development projects. The participatory process also depends on NGOs and community level self-help groups (private).

The institutional framework of participatory irrigation management (PIM) in which the local stakeholders participate commenced in 1995, introduced a three-tier management structure for irrigation systems. This involved creating tertiary-level Water Management Groups (WMGs; each consisting of nine members—three from each of three farm-size categories: 'large', 'medium' and 'small'); secondary level Water Management Associations (WMAs; consisting of 10-15 WMGs); and a Water Management Federation (WMF) at the highest level of a system. Water Management Organisations are responsible for planning, implementing, operating as well as maintaining local water schemes in a sustainable way. They also contribute towards the capital and operating costs of the scheme as decided by the Government or on a voluntary basis acting in their own interest.

Ownership of flood control drainage irrigation (FCDI) projects with command area of 1000 ha or less is gradually transferred to the local governments with the ones that are satisfactorily managed and operated by the beneficiary/community organisations. The management of public water schemes with command area of up to 5000 ha are gradually made over to local and community organisations and their O&M are to be financed by local resources. Public water schemes with command area over 5000 ha are gradually given to private management through leasing, concession, or management contract under open competitive bidding or jointly managed by the project implementing agency along with local government and community organisations.

Appropriate public and private organisations provide information and training to the local community organisations for efficient management of water resources. For minor irrigation stakeholders participation is confirmed by their willingness to commit to financial contributions before receiving services. In case of FCDI projects water rates are charged for O&M as per government rules. Water charges realised from beneficiaries for O&M in a project are retained locally for the provision of services within that project. Some use an informal structure while others use a formal structure with legally registered organisations according to the guidelines for participatory water management.

BADC during its programme to expand groundwater irrigation required WUGs to be formed. The Barind Multipurpose Area Development Project has successfully used cooperatives for water management. The Ministry of Agriculture has a shared experience in participatory management under National Minor Irrigation Project (NMIP) where beneficiaries voluntarily re-excavated canals to support LLP irrigation. The Department of Public Health Engineering has also introduced participatory management to support rural water supply and sanitation program. An important development in participatory management has been in Small Scale Water Resources Development Project of LGED. The beneficiaries have participated in the water management projects right through its initiation by making a percentage payment toward investment and for operating and managing the project entirely by them.

Much effort was given in the past two decades to review stakeholders' participation under the Dutch aided Early Implementation FCD projects, and IDA (International Development

Assistance)/CIDA (Canadian International Development Assistance) assisted small-scale FCDI projects. This initiative was later enforced through Flood Action Plan (FAP) studies and the System Rehabilitation Project (SRP) of the BWDB. Lately, the LGED started developing small irrigation projects having an area less than 1000 ha in order to improve efficiency and coordinate better with other infrastructure building efforts.

However, except for a very few, the experience of participatory management has been a mixed one. Progress in creating and developing these user groups has been slow, and the irrigation sector continues to be managed at all levels by public-sector agencies. Perhaps, it is due to some gap at the initial stage of the project preparation where it might not have been possible to involve the beneficiaries at all stages of project cycle. Although the guidelines for participatory water management are an excellent starting point to promote local stakeholder involvement in water management infrastructure these are inadequate in promoting meaningful participation (WB, 2006). Rather than establishing the mechanisms to improve agencies ability to respond to local stakeholders, the guidelines encourage the participation from the perspective of achieving the objectives of the executing agencies.

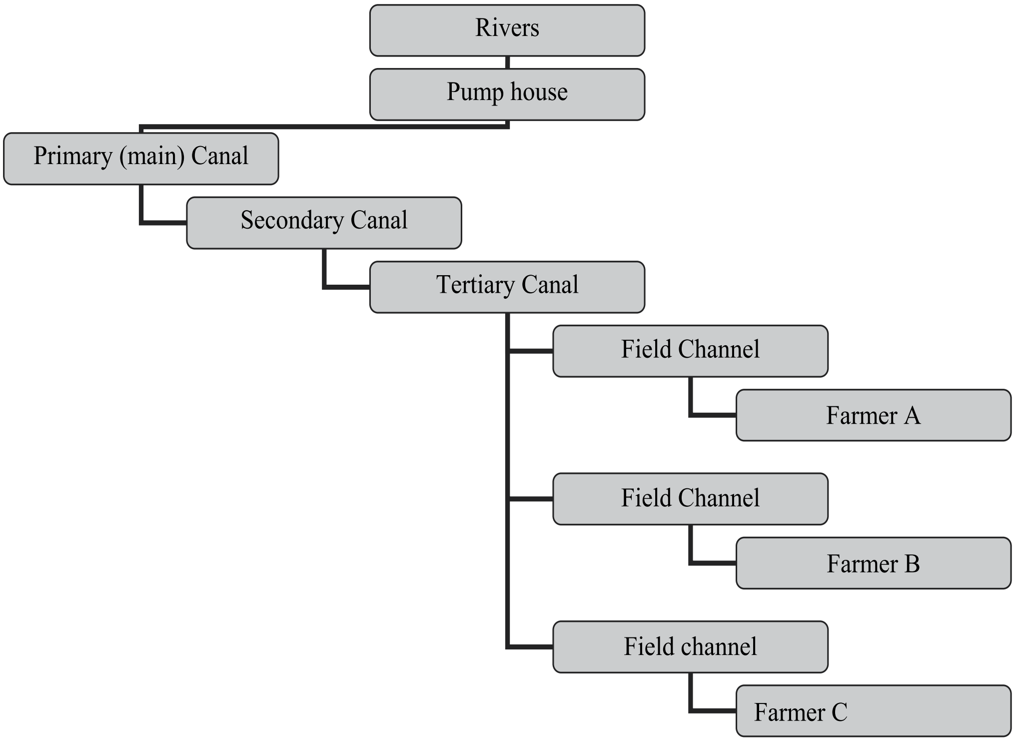


Fig. 2. National Surface Water Irrigation Distribution Systems

Individual farmers get water in their fields through the field channels. Farmers are responsible for maintaining the field channels from the tertiary canals.

Some case studies

There are 3 types of institutional models for large scale surface water irrigation schemes in Bangladesh. The BWDB controls Meghna-Dhonagoda Project and Pabna Irrigation Project down to the tertiary outlets and work with the registered user groups organised in several tiers under the cooperative system. The user groups collect water charges and participate in overall scheme management and operation and maintenance. Asian Development Bank (ADB) supports these schemes. Also irrigation schemes are managed by an authority like BMDA.

Pabna Irrigation and Rural Development Project (PIRDP) is located on the floodplain of the Brahmaputra and Hurasagar rivers (west-central Bangladesh). This project aimed to provide flood control, drainage, and irrigation facilities. The total project area is 186,000 ha and the area irrigated is 145,000 ha. 77 percent of the total rainfall occurs between mid June and mid October. Rice is the major crop grown on 64 percent of the total cropped area. Other crops are pulses, potato, jute, sugarcane, vegetables, onion, wheat and oilseeds. Land is inequitably distributed average landholding is 0.92 ha. 6% of landowning households own 25% of the available land and 14% households are landless. 78% households own 1 ha of land or less. The average annual incomes of small-, medium-and large-scale farmers are USD 487, USD 846 and USD 1,347, respectively. The net value of crops produced per ha is USD 203. The net benefit of irrigation is USD 125/ha. The irrigation benefits mainly result from access to water and use of HYV technology on the irrigated land. Farmers with very small landholdings (less than 1 ha) obtained higher yields per ha than larger landholders. This is because the land-poor farmers use the available water more efficiently, grow HYVs of rice on a greater proportion of their land, and irrigate more intensively than farmers with more land.

Only 2 of the 365 WMGs formed have been registered with the government. These groups do not assess or collect irrigation charges, or dictate how the revenues are spent. These functions are still being performed by the BWDB. Since user groups have not yet taken on this role, as originally envisioned, collection rates remain very low, 9% of the target. Water charges are not based on the volume of water used, but on (1) the area irrigated (irrespective of the size of the farm), and (2) the type of crop grown (depending upon its water requirements). Charges average around BDT 540/acre (USD 22.39/ha).

The **Thakurgaon Irrigation Project** consists of a cluster of deep tube wells and is transferred to a private company established by the local stakeholders who sells water on a pay as you use system. The project is now running successfully where payments are made in advance to pump operators at a specified unit rate and they provide water to the farmers within the command area according to the terms of payment on a first come first served basis. The system provides for long term management, operation and maintenance for the equipment.

In case of **Muhuri Irrigation Project** there is no functioning organisation of local stakeholders and also there is no opportunity for minor irrigation development. Therefore large scale surface water management infrastructure is the only alternative and the project infrastructure provides farmers with flood control and access to surface water for irrigation through a network of secondary channels. As the system does not extend to the tertiary level and beyond development costs are lower but farmers are responsible for obtaining, operating and maintaining their own pumps to abstract water from these channels and for the associated field distribution systems. However the major infrastructure constructed was of good quality and continues to function effectively and provide the anticipated benefits.

At present the best institutional model is the ADB financed Small Scale Water Resources Development Sector Project which provides flood control, drainage or irrigation infrastructure to subproject areas less than 1000 ha. These projects rely heavily on local stakeholders' initiative to identify interventions, ratify engineering designs, demonstrate commitment to operate and maintain the infrastructure by contributing a specified amount of funds in advance of physical construction. The projects are implemented by the LGED with support from the ADB and the Government of Netherlands. In some cases low quality infrastructure, shortcuts in the development process and inconsistency are responsible for failure. In order to make water management investments pro local stakeholders' financial responsibility, decision-making authority and accountability must be transferred to local stakeholders and their representatives – the local government. Investments have to be structured so that service agencies are obligated to cater the end users requirements.

2.2 Private sector groundwater irrigation

After 1974 many surface water irrigation projects like the GK project became ineffective due to operation of the Farakka Barrage. Also these projects had long gestation periods, suffered from management and maintenance problems and were unpopular with farmers because the distribution canals took up scarce land. In 1980s, there was a surge in private sector involvement in ground water extraction mostly by shallow tube wells. At present the role of BADC is very minimal. Over time the government shifted emphasis to small scale projects, fielding power pumps to lift surface water from creeks and canals and tube wells for extraction of groundwater. Since then many farmers switched to 2 rice crops and vegetables and other crops which require much less water instead of 3 rice crops during the *boro* season and also moved to shallow tube wells instead of deep tube wells. This was the time when government emphasised groundwater irrigation.

Private sector groundwater development for irrigation has been instrumental in expanding agricultural output. It is also recognised that the development of groundwater for irrigation has virtually required no public sector financing in contrast to a huge capital cost of surface water systems ranging from USD 500 to 1800 per ha. Capital investment in the Teesta Project was about USD 250 m in 1985 to develop 100,000 ha of irrigation. It is further recognised that farmers readily mobilise the financial and technical resources to operate and maintain groundwater irrigation infrastructure whereas in surface water systems, in most cases the cost of irrigation user fee collection has exceeded the fees collected. The NWMP also notes that irrigation intensities are low on the 15 major existing irrigation schemes. On the whole, the large scale surface water irrigation projects do not have a good performance record. Minor irrigation is a source of net revenue (diesel tax revenue less electricity subsidies). Diesel is used to power about 90 percent of pump sets and irrigates 70 percent of the area. Electricity powers the rest. Present price policy subsidise electricity while diesel is taxed. As the end user farmers own the equipment and usually provide irrigation water to neighbouring plots at competitive prices. Infrastructure quality, management and operation, maintenance and benefits are not issues. The individual owners ensure that their requirements for the equipment and its use are met.

Irrigation has expanded to more than 50 percent of cultivated land (Hossain et al, 2007) and is provided through minor irrigation devices such as low lift pumps (LLP), shallow tube wells (STW) and deep tube wells (DTW). Initially LLPs, DTWs and STWs were supplied by Bangladesh Agricultural Development Corporation (BADC) a public sector organisation.

Since the early 1980s the government has privatised the procurement and distribution of minor irrigation equipments, reduced import duties and removed the restriction on the standardisation of irrigation equipments. As a result farmers have made substantial investment in shallow tube wells and power pumps contributing to rapid expansion of irrigation facilities since the mid-1980s. The area irrigated by tube wells expanded from 53, 000 ha in 1973 to 3.3 m ha in 2000 (Hossain et al, 2007). Shallow tube wells and power pumps accounted for 71 percent of total irrigated area in 2000. Small scale private investment on low lift pumps and tube wells and development of a competitive market for water transactions from tube wells to small and marginal farmers accelerated rapid expansion of irrigation. The diffusion of modern variety *boro* rice is strongly related to groundwater irrigation expansion. After the privatisation of minor irrigation LLPs and STWs became more popular compared to DTWs which required high initial investments.

Bangladesh is a delta composed of ridges and troughs. Soil texture is heavy on troughs and light on ridges. Plots on high land have different cropping patterns due to different soils, flooding regimes and access and returns to irrigation sources compared to medium and lowland (Palmer-Jones, 2001). Water loss from canals is high on more elevated land with light textured soils. Low land is suitable for rice cultivation since it is permanently waterlogged. Returns to irrigation are spatially variable due to soil and hydro-geological characteristics.

Modern irrigation mainly consists of STW which has almost replaced LLPs and is gradually displacing DTWs which are economically and socially unfavourable. The remaining DTWs although initially set up as either formal or informal cooperatives have become privately owned.

There are various institutional forms of ownership and management of STW. Many STWs are jointly owned by relatives, neighbours or friends. Usually a pump operator is engaged for the whole irrigation season who may also be the owner or one of the users for a fixed seasonal fee in cash or kind. In many places water is paid by one fourth of the gross crop harvested and delivered to the tube well owner. A large part of capital costs and operation and maintenance costs come from outside the village like business, service and remittances.

In Bangladesh informal water markets for irrigation have developed quickly with the rapid expansion of tube well irrigation over the last decade. In case of shallow and deep tube wells, the owners of the irrigation equipment enter into deals for irrigation services with neighboring farmers in addition to using the equipment for irrigating their own land. With the expansion of water markets in the private sector, the pricing system has also undergone changes to suit varying circumstances. There is no single rate or uniform method for payment of irrigation water. Per hectare water rates vary not only from one area to another but also depend on the type of well within a particular area (Biswas and Mandal, 1993).

In the initial stage, the most common practice was sharing one-fourth of the harvest with the owner of the equipment in exchange for water. That gave way to a flat seasonal fee, the rate depending on the availability of electricity and the price of diesel. In recent years, the market has moved toward fees per hour of tube well operation. In Bangladesh, the major source of irrigation is the shallow tube wells and power pumps mostly run by diesel as many places in rural Bangladesh still do not have electricity connection. Diesel pumps usually have higher costs and lower water extraction capacity than electricity operated pumps (Wadud and White, 2002). Diesel being a major agricultural input in the cultivation of *boro* rice, the cost of *boro* cultivation is very sensitive to the price of diesel.

Type	STW		DTW	
Name	Shallow tube well		Deep tube well	
Description	Shallow well with suction mode pump		Usually turbine type pump (in large diameter) well 150-300m deep	
Energy	Diesel	Electricity	Diesel	Electricity
Nominal Capacity (litres/second)	12	12	50	50
Overall efficiency	25%	35%	35%	35%
Energy Cost (BDT) per ha	4,040	1,570	5,410	2,950
Total cost (BDT) per ha	6,990	3,770	12,940	8,930

Note: Irrigated area assumes 10 hours pumping daily and energy costs are based on diesel fuel costs of BDT 14/litre and electricity at BDT 25/KWh. Capital cost is annual equivalent capital cost at 12% discount rate divided by the command area. 1 USD = 69 BDT (Bangladesh Taka).
Source: WARPO (1999).

Table 1. Estimated Total Costs for Different Well Technologies

For Bangladesh the cost of production is higher for the *boro* rice than for the *aman* variety of rice. A major factor behind the high unit cost of *boro* rice cultivation in Bangladesh is the high cost of irrigation compared to the other countries in the region. Bangladeshi farmers have to spend about USD 51 in irrigating one-hectare land whereas the irrigation costs are about USD 32 in Punjab, India (Hossain and Deb, 2003). The cost of MV *boro* irrigation is even higher in Bangladesh; it is USD 117.6 per ha (Hossain and Deb, 2003). In Bangladesh, irrigation costs account for 28 percent of the variable costs of rice cultivation.

Further, in Bangladesh there has been a rising dependence on groundwater due to lack of surface water in the recent past. Overexploitation of groundwater for irrigation and other purposes has lowered the water table in many parts of the country below the suction level of the tube wells. The result is the increased costs for irrigation. Based upon the field study, NWMP (National Water Management Plan) estimates of operating costs for supplying 11,000m^3 of water (the typical gross demand for 1 ha of *boro* rice) are given in Table 1. The costs of diesel operation are substantially higher than electricity. Part of this is due to the generally lower efficiency of diesel-powered pump sets, but the major cause is that diesel fuel is taxed whereas electricity is charged at a price lower than its production cost. On the other hand, India provides heavy subsidy on electricity that lowers the cost of irrigation. In Indian Punjab electricity is provided free for tube well irrigation and the farmers are also provided free water from irrigation canals.

The present government policy for water management is the conjunctive use of surface and groundwater. Government and donors agree on policies to promote the expansion of irrigation from groundwater using tube wells provided by the private sector. According to the National Water Policy water should be used most economically. Farmers do not pay for volume used for irrigation but pay for the operation and maintenance. They pay for digging canals, diesel, electricity, labour charges for running pumps etc. At present 90 percent of total irrigation of 4.5 m ha is from groundwater, the rest is from surface water mainly

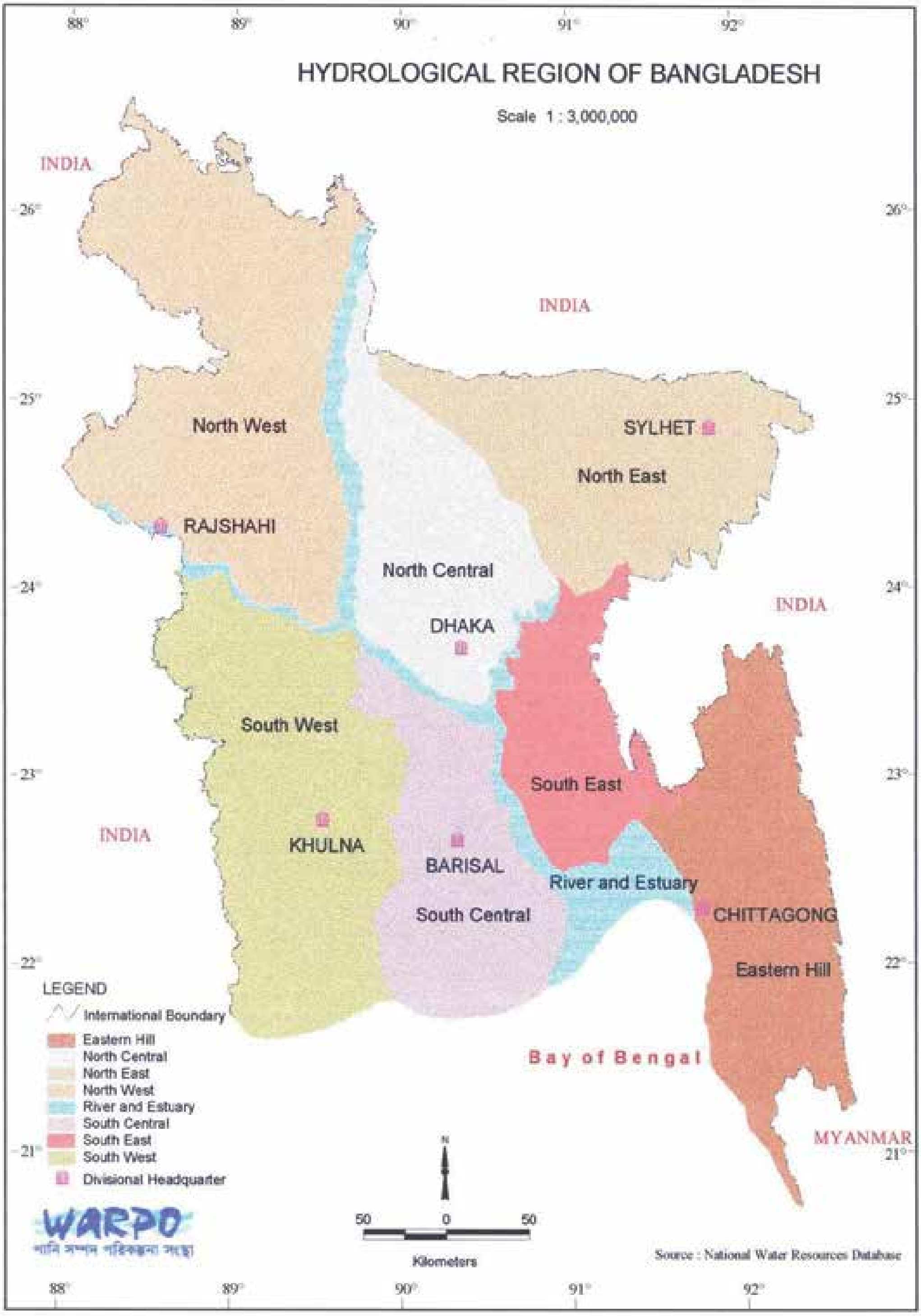


Fig. 3. Hydrological Regions of Bangladesh

because during the irrigation season (winter) there is no surface water due to upstream use. Mining and over-extraction is lowering groundwater table which is recharged only during floods. The National Water Management Plan emphasises to improve management of existing surface water irrigation schemes. It would support minor irrigation through improvement of shallow tube well and deep tube well diesel engine fuel efficiency, introduction of lower cost pump sets and improvement of irrigation distribution to reduce losses in water short areas.

3. Study area: Northwest region

The objective of this study is to measure the volume of irrigation water and find the actual price of irrigation water per unit used by farmers for alternative modes of irrigation in the Northwest region (NW) of Bangladesh. Water is most scarce in the Northwest and Southwest region during the dry season due to low annual rainfall. The problem is more complicated in the Southwest region due to water logging and salinity intrusion from the Bay of Bengal in addition to low annual rainfall. Hence I have chosen the Northwest region in order to isolate the impact of dry season scarcity of water from other seasonal and environmental problems. Previous studies (Chowdhury, 2005; Linde-Rahr, 2005) used total irrigation costs instead of water as a physical input since there was no information on the price per unit of water or volume of water used in the dataset. Through focussed group discussion we collect data on volume of water used in irrigation in addition to costs of irrigation in 3 districts of the NW region.

Bangladesh is an agricultural country divided into 7 hydrological regions. Northwest region encompasses the Rajshahi Administrative Division of 16 districts and is bounded by the Brahmaputra and Ganges rivers. Apart from Rajshahi Rangpur, Dinajpur, Bogra and Pabna are the main urban centres. Average rainfall is about 1700 mm but its south western part in the Barind zone is one of the driest in Bangladesh with average rainfall below 1400 mm. The Barind Tract is the driest part of the region where surface water supply is very limited. The tract extends over Rajshahi, Dinajpur, Rangpur and Bogra districts of Bangladesh and Maldah district of West Bengal, India. The temperature varies between 6 and 44 degree Celsius. Apart from the monsoon from mid June to mid October the climate is very dry. The high Barind is the only elevated land.

The Barind Tract is distinguished by hard red soils and older alluvial deposits which are different from other parts of Bangladesh. The main clay minerals are kaolinite, chlorite, smectite, and mica-smectite interlayered phases. The Barind clay contains an average total organic carbon content of 0.05%. The agro climatic conditions of the Barind region are highly favourable for irrigation but required an enormous government support before this potential could be realised.

Irrigation in the northwest region is almost entirely dependent on groundwater. Its net cultivable area is 2.35 m ha. The region is highly developed agriculturally with the largest irrigated area of all regions supplied mainly by shallow tube wells. Initial experiments with tube well irrigation began in the 1960s with the Thakurgaon Deep Tube well Project in the northwest. Due to STW pumping irrigation seasonal water table decline is widespread. The southern part of this region is very flood prone. Some of the country's biggest flood control drainage and irrigation schemes are located in this area. These are Teesta Barrage, Pabna Irrigation Project, and the Barind Multipurpose Development Authority (BMDA). BMDA includes a deep tube well irrigation component.

In the 1990s except the special case of the Barind project government withdrew any involvement in groundwater irrigation. An independent autonomous body, the Barind Multipurpose Development Authority was established to implement the projects under the direct supervision of the Ministry of Agriculture. The main objective was to improve the quality of life of the people by ensuring year round irrigation, augmentation of surface water resources, improvement of agricultural support services etc. Currently the Barind aquifer is supplying sufficient water for extensive irrigation. The project is developed with meagre international support either in terms of experts or finance. There are active staffs, good management and farmers participate enthusiastically because their well being is greatly enhanced by these developments.

Variety	Classification	Growth duration (days)	Yield per ha (ton)
BR29	medium fine	165	7.5
BR16/Shahi balam	fine	165	6
BR14/Gazi	medium coarse	160	6
BR11/Mukta	medium coarse	145	6.5
BR28	medium fine	140	5
BR1/Chandina/Chaina	coarse	150	5.5
BR9	medium coarse	155	6
BR36	fine	140	5

Table 2. *Boro* Rice Varieties

There are 18 varieties of *boro* rice being cultivated in the Northwest region. I classify them into 3 broad categories fine, medium and coarse with the help of Bangladesh Rice Research Institute Scientists. Although evapo-transpiration is the true water requirement for crop growth crop water requirement for rice equals seepage, percolation and evapo-transpiration. Rice plants require continuous water in addition to land preparation. About 200 mm (heavy soil) to 250 mm (light soil) water is required for land preparation in *boro* rice cultivation. Therefore irrigation water requirement for *boro* rice is 3 times higher than non-rice crop like wheat and maize. Usually the seepage and percolation rate in rice fields varies from 4 to 8 mm per day (Rashid, 2008). Seepage and percolation rates are higher for light than heavy soil.

The rate of water requirement varies with atmospheric condition (temperature, rainfall), soil type, crop age, duration of the crop growth, land elevation and water management status in the plot. No irrigation is required before 10-15 days of harvest. Water balance studies show that much more water is supplied by irrigation than is required for evapotranspiration, seepage and percolation. According to one BRRI study 4,000 litres of water is used as irrigation for per kg *boro* rice in farmers' field compared to 2,000 litres in an experimental plot. Irrigation water requirement for *boro* rice production also varies with the varieties of longer duration.

Rice variety	Growth duration (days)	Water required for heavy soil (mm)	Water required for light soil (mm)
BR28 (medium duration)	140	995	1355
BR29 (long duration)	160	1205	1640

Table 3. Water Requirement for *Boro* Rice under Continuous Standing Water

	Boro rice	Wheat/non-rice cultivation	STW (shallow tube well)	DTW (deep tube well)
Northwest region	BDT 7000-8000 per ha	BDT 50-60 per hour		
Dinajpur	BDT 2500 per ha*	BDT 35-45 per hour *	BDT 30-60 per hour for wheat	
Rajshahi	BDT 7000 per ha**	BDT 1852 per ha**	BDT 50 per hour ***	BDT 75-80 per hour***

Source: As available from various BARC (Bangladesh Agricultural Research Council) Reports, 2001.
* in a village in Dinajpur district (NW region).
** Barind area (NW) in 1998-99.
*** In *boro* season.

Table 4. Cost of Irrigation in BDT for different Districts of NW region

Irrigation cost is different for different crops. Most popular is one-fourth of the crop share for irrigation in paddy cultivation. Pump owners provide the fuel and oil. Since it leads to a flat seasonal fee and sometimes overuse of water resulting in higher marginal cost per unit water extraction, it is important that we have information on volume of water used in irrigation in farmers' field.

4. Methodology: Focussed group discussion

International Rice Research Institute (IRRI) conducted an Agricultural Household Survey in Bangladesh in 2000, 2004 and 2008 for 3 crop seasons and collected data on costs of inputs (including irrigation water) and returns on investment from a nationally representative sample of 1880 farm households from 62 villages belonging to 57 of 64 districts of Bangladesh. But the data do not have any information on the volume of irrigation water used in the fields or price per unit. Irrigation is the total irrigation costs measured in BDT (Bangladesh Taka) and we do not know the price per unit of water or the number of hours the pump is used for pumping water. The data available are for total cost of irrigation per household. The costs of irrigation are basically the costs of pumping water. Farmers mainly use low lift pumps for pumping water from surface water sources and shallow and deep tube wells from aquifers and groundwater. I conducted a focussed group discussion in the Northwest region to validate the IRRI data findings about irrigation costs and gather some information about the per unit water costs/prices they bear/pay for using different types of irrigation mentioned earlier. Focussed group discussion is useful in case of small samples as opposed to other methods for gathering information within a short time.

The task was to collect some samples of data on water costs/prices per acre for *boro* rice from representative farmers who are using 5 different types of irrigation options in the NW region. These irrigation modes are low lift pump, shallow tube well, deep tube well, canal irrigation project of the government and local or traditional irrigation system. Data were collected on farmers' use of irrigation water, volume, price they pay for hiring pumps, if they own pumps its cost of operation run by diesel or electricity, daily hours of pumping water during the irrigation season, capacity of pumps to extract water per second in litres etc. If it is a government owned irrigation project then the same information is collected on low lift pumps and other modes of irrigation the farmers are using. I also gathered information on the water table there. Three districts are Rangpur, Rajshahi and Pabna.

Rangpur represents northern range or highland, Rajshahi is from Barind Tract representing medium high land and Pabna represents lowland. In Rangpur besides the private sector there is Teesta irrigation project. In Pabna district there are government run irrigation projects like Pabna irrigation project plus privately owned pumps. Pabna Irrigation Project is mainly based on surface water irrigation. In Rajshahi the major irrigation projects are run by the Barind Multipurpose Development Authority. From these 3 districts 15 farmers using 5 different types of irrigation options were interviewed. Thus the focussed group discussion is for 15 farmers. The results are summarised in the following table.

District	Village	Respondent	Land under boro rice	Harvest	Irrigation type	No of irrigation	Inches of water per bigha	Cost of Irrigation	Energy source
Rajshahi	Achua taltola	1	1 acre	45 maunds	Deep tube well	13	2.5	BDT 3600 per acre	Electricity
Rajshahi	Moishalbari	2	1.67 acre	75 maunds	Shallow tube well	15	1.5	BDT 3600 per acre	Electricity
Rajshahi	Moishalbari	3	2 acre	72 maunds	Low lift pump	15	1.5	BDT 4500 per acre	Electricity
Pabna	Bhabanipur	4	0.33 acre	25 maunds	Deep tube well	65	3	1/4th	Electricity
Pabna	Jobedpur	5	3.33 acre	200 maunds	Deep tube well	120	3	BDT 6000 per acre	Electricity
Pabna	Jobedpur	6	1 acre	36 maunds	Shallow tube well	75	2	1/4th	Electricity
Pabna	Sonatola	7	3.67 acre	308 maunds	Low lift pump	105	3	BDT 3600 per acre per m+1500	Diesel
Pabna	Sonatola	8	2.33 acre	180 maunds	Traditional method	100	2.5	BDT 1500 per month	
Pabna	Nandanpur	9	1.33 acre	65 maunds	Canal irrigation	65	4	BDT 540 per acre	
Rangpur	Shyampur	10	5 acre	60 maunds	Deep tube well	20	2	BDT 700 per acre+m salary	Electricity
Rangpur	Pakuriasharif	11	1 acre	100 maunds	Deep tube well	30	3	BDT 3181.81 per acre	Electricity
Rangpur	Godadhar	12	5.5 acre	280 maunds	Shallow tube well	35	3	BDT 2800 per acre	Electricity
Rangpur	Nabanidas	13	3 acre	225 maunds	Shallow tube well	45	4	BDT 4545.45 per acre*	Electricity and diesel
Rangpur	Dighaltari	14	2 acre	100 maunds	Shallow tube well	64	5	BDT 3600 per acre per week	Diesel
Rangpur	Dighaltari	15	3.33 acre	250 maunds	Canal irrigation	30	5	BDT 900 per acre	Hand tube well

*BDT 2727.27 per acre if run by electricity
1 maund =28 kg
1 hectare = 2.47 acre
1 acre = 3 bigha
1 bigha-inch = 20,588 litres

Table 5. Results from my Field Study in the Northwest Region

In Rajshahi most of the irrigation pumps are installed and maintained by the BMDA. We interviewed farmers in 2 villages of Godagari Upazila using STW, DTW and LLP in Sharmongla canal irrigation project. The Barind Authority owns the DTW and the LLP. The LLP user here incurs more cost than the DTW and the STW users per acre. All the pumps are run by electricity. We did not however find anyone using traditional or local irrigation method in Rajshahi.

In Pabna I interviewed 6 farmers and found that two farmers pay the irrigation cost in terms of crop (1/4th). Here we find a very high frequency of irrigation in case of one DTW user and in general all 6 farmers compared to the farmers of Rajshahi and Rangpur. These farmers are producing BR29 and IRRI29 *boro* varieties which have longer duration. The soil quality may be also lighter than that in Rangpur and Rajshahi which requiring more water. DTW has the highest cost of irrigation. Electricity or diesel cost and the monthly wages of the pump operator constitute the total costs of irrigation for those who are using DTW, STW and LLP. Traditional method and canal irrigation system are cheaper modes of irrigation. In Rangpur the frequency of irrigation is found lower than Pabna but higher than in Rajshahi. I interviewed 6 farmers in Rangpur. Here we found an interesting case where one farmer who is running a STW for irrigation is using both electricity and diesel in the absence of electricity. In this case it is noteworthy that irrigation cost is less than double when he has to use diesel as fuel instead of electricity.

Lessons from the focussed group discussion

According to this field research one can get the information on water volume in two ways. One is from the horsepower of the pump, the number of hours the machine is run and another way is the number of inches of water on the plot. As it is not possible to know the level of efficiency of the pumps that are operating it is more reliable to measure the quantity of water used from the number of inches of standing irrigation water on the field. We did not however find anyone using traditional or local irrigation method in Rajshahi.

It is obvious from these interviews that farmers cannot reveal the amount of water withdrawn per minute or hour when they are running the pumps to irrigate their fields. However one can estimate the amount of water from the inches of standing water on their fields each time they irrigate their plots which is clear from this small sample survey.

Farmers prefer traditional method to government canal irrigation project to STW to LLP to DTW the cost of whichever is less. Electricity run pumps always cost a bit more than half the amount of diesel run ones. The use of traditional/local method, canal irrigation project and LLP depends on the availability and proximity of surface water. When groundwater is the only choice STW is preferred to DTW from the view point of least cost as investment in DTW is lumpy in nature. DTW is beyond the means of the poor mass of the farmers to be single owners. But in some cases DTW can be cheaper to an individual due to large economies of scale. Government run/maintained DTWs cost less to farmers than DTWs run on the basis of joint ownership and the rented ones. Cost of irrigation for pumps is the energy cost and the salary of the pump manager if hired or maintained by the government. The monetary cost has to be weighed against pump management and electricity availability.

For traditional (local) irrigation method the cost of irrigation is the maintenance of the apparatus and the cost of hired labour if any. For the government run canal irrigation methods the farmers usually pay a fixed amount per unit of irrigated land per crop during the season and in case of participatory water management water user groups pay for maintenance of field channels plus management cost in some cases. It varies from case to case. It is more reliable to measure the amount of irrigation water in terms of bigha inch water and the number of times the rice field is irrigated. In many cases farmers or even some pump managers cannot tell the level of efficiency of the pumps they are running. Only farmers who also happen to be pump owners/managers at the same time could give us accurate information about the age and the durability of the irrigation pumps.

5. Conclusions

Farmers in Bangladesh do not pay for use of per unit of irrigation water. When surface water was abundant farmers solely depended on rivers, canals and ponds to irrigate their fields with traditional local methods where the maintenance cost of the apparatus and labour charges were the costs of irrigation. For the government run canal irrigation methods the farmers usually pay a fixed amount per unit of irrigated land per crop during the season and in case of participatory water management water user groups pay for maintenance of field channels plus management cost in some cases. It varies from case to case. With the advent of groundwater irrigation cost of irrigation consists of maintenance of the pumps, fuel cost (electricity or diesel) and the salary of the pump mechanic when required. Farmers use low lift pump to pump water from surface water sources and shallow or deep tube wells for groundwater. The use of low lift pump is limited by the availability of surface water in the canals and rivers during the dry season. Since investment in deep tube well is lumpy in nature farmers prefer shallow tube wells. In case of shallow tube wells the energy cost (electricity or diesel) is the main component of irrigation cost. As electricity is not available in all the villages farmers have to depend on diesel to run irrigation pumps to a large extent. Hence the price of diesel in the international market plays a crucial role in cost of irrigation for the private sector.

The main challenge of public sector irrigation institutions is to design proper incentives for all stakeholders to participate in the participatory water management network. Successful water management practice for irrigation will depend on equitable participation of all groups of farmers as water user groups in management and cost recovery. Introduction of rice varieties that require less water for irrigation per ha is mandatory. Government should give incentives or price support for wheat and maize production so that farmers diversify towards these crops that require much less water per ha for irrigation compared to *boro* rice. In order to run the pumps with electricity stability in power supply is a must that will reduce the cost of irrigation as well as cost of cultivation drastically. In this endeavour there is no alternative to 100 percent rural electrification. More case studies or field research with large samples will demonstrate the actual status of irrigation institutions from the perspective of policy design and implementation specially if successful examples are identified and replicated elsewhere.

6. Acknowledgements

This paper has benefited from many comments and suggestions of Professor A K Enamul Haque. I am also grateful to Professors Mustafa Alam, Syed M Ahsan, Dr Priya Shyamsundar, and other SANDEE (South Asian Network on Development and Environmental Economics) Advisors for their comments. Dr Mahabub Hossain, Executive Director, BRAC (Bangladesh Rural Advancement Committee) kindly gave me the permission to rent rooms in their training and resource centres in Rangpur, Rajshahi, and Pabna during my field research in the villages. The study grant from SANDEE is gratefully acknowledged. Finally I express my sincere gratitude to Economic Research Group (ERG) for hosting this study grant.

7. Appendix

Questionnaire

First part of the questionnaire constitutes socio-economic information of the farmers.
Name of the respondent
Relationship with the household head
Gender
Age
Village
Union
Upazila
District
Level of education
Other occupation of the household and the members
Total land owned by the household
Per capita annual income of the household
Village with electricity connection: yes/no
Second part includes farming and irrigation related information.
Total land cultivated
Terms of lease: own, shared, leased in, leased out
Crops produced
Area under boro rice cultivation
Type of boro rice (variety)
Quantity harvested in kg
Quantity sold in kg
Price obtained per kg
Source of irrigation (own tube well, shared tube well, hired tube well, low lift pump, shallow tube well, deep tube well, government irrigation canal project, local irrigation system)
Type of tube well (submersible or non submersible)
Name of owners (both own and joint)
Year of installation
Depth of bore hole, filter and pump
Depth of water level
Horsepower of the pump
Cost of installation
Whether run by diesel or electricity
Costs of diesel or electricity
How the energy costs are shared
Whether labour/mechanic is required to pump water (yes or no)
If yes, his charges
The depth of water in inches on the ith irrigation

Number of hours on the ith irrigation taken to flood the field to reported number of inches
Terms of irrigation when the source is a shared tube well
Terms of rent when the pump is hired
Distance of the plot from the irrigation source

8. References

Ahmad, Q. K., A. K. Biswas, R. Rangachari and M. M. Sainju edited (2001): *Ganges-Brahmaputra-Meghna Region: A Framework for Sustainable Development,* University Press Limited, Dhaka, Bangladesh.

Asian Development Bank (2004): Pro- poor Interventions in Irrigated Agriculture Issues, Options and Proposed Actions, Bangladesh, Document of the Asian Development Bank.

Banerji, A. and J.V. Meenakshi (2006): Groundwater Irrigation in India: Institutions and Markets, SANDEE Working Paper 19:06.

BARC (2001a): Bangladesh Agricultural Research Council, Contract Research Project on Improvement of the Water Resources Management for a Sustainable Rice-Wheat system in Dinajpur and Jessore Areas, Irrigation and Water Management Division, Bangladesh Agricultural Research Institute, Gazipur-1701, November 2001.

BARC (2001b): Bangladesh Agricultural Research Council, Contract Research Project on Improvement of the Water Resources Management for a Sustainable Rice-Wheat system in Barind Area, Irrigation and Water Management Division, Bangladesh Rice Research Institute, Gazipur-1701, December 2001.

Biswas, M. R. and M. A. S. Mandal (1993): *Irrigation Management for Crop Diversification in Bangladesh*, University Press Limited, Dhaka, Bangladesh.

Chowdhury, N. T. (2005): "The Economic Value of Water in the Ganges-Brahmaputra-Meghna River Basin", Beijer Discussion Paper 202, October 2005, Beijer International Institute of Ecological Economics, the Royal Swedish Academy of Sciences, Stockholm, Sweden. Available at www.beijer.kva.se/publications/pdf-archive/Disc202.pdf

Chowdhury, N. T. (2010): "Water Management in Bangladesh: An Analytical Review", *Water Policy, 12(1),* 32-51.

Government of Bangladesh (2005): Unlocking the Potential National Strategy for Accelerated Poverty Reduction, General Economics Division, Planning Commission, and Government of the People's Republic of Bangladesh.

Hossain, M., D. Lewis, M. Bose and A. Chowdhury (2007): Rice Research, Technological Progress and Poverty: The Bangladesh Case in *Agricultural Research, Livelihoods, and Poverty, Studies of Economic and Social Impacts in Six Countries.* The Johns Hopkins University Press, Baltimore, USA.

Hossain, M. and U. K. Deb (2003): Trade Liberalization and the Crop Sector in Bangladesh, Paper 23, the Centre for Policy Dialogue, Dhaka, Bangladesh.

Kijne, J.W., T. P. Tuong, J. Bennett, B. Bouman and T. Oweis (2003): Ensuring Food Security via Improvement in Crop Water Productivity, Challenge Program on Water and Food Background Paper 1.

Linde-Rahr, M. (2002): Household Economics of Agriculture and Forestry in Rural Vietnam, Ph. D thesis, Gothenburg University, Gothenburg, Sweden.

Ministry of Water Resources, GOB (2001): Guidelines for Participatory Water Management, Dhaka, Bangladesh.

Molden, D. and R. Sakthivadivel (1999): Water Accounting to Assess Use and Productivity of Water, *Water Resources Development*, *15*, 55-71.

Mukherji, A. (2004): "Groundwater Markets in Ganga-Meghna-Brahmaputra Basin: Theory and Evidence", *Economic and Political Weekly*, 3514-3520.

Palmer-Jones, R. (2001): Irrigation Service Markets in Bangladesh: Private Provision of Local Public Goods and Community Regulation? Paper prepared for the Workshop on Managing Common Resources at the Department of Sociology, Lund University, Sweden.

Rashid, M. A. (2008): Growth Phase-wise Water Requirements of Rice, Irrigation and Water Management Division, Bangladesh Rice Research Institute (BRRI), Gazipur, Dhaka, Bangladesh.

Rogers, P., R. Bhatia and A. Huber (1998): Water as a Social and Economic Good: How to Put the Principle into Practice, paper prepared for the meeting of the Technical Advisory Committee of the Global Water Partnership in Namibia.

Shahabuddin, Q. (2002): Position Paper on Water Resources Development for the Sixth Five Year Plan (2002-2007), General Economics Division, Planning Commission Ministry of Planning, Government of the People's Republic of Bangladesh.

Vaidyanathan, A. (2004): Efficiency of Water Use in Agriculture, *Economic and Political Weekly*, 2989-2996.

Wadud, M. and B. White (2002): The determinants of technical inefficiency of farms in Bangladesh, *Indian Economic Review*, *37*, 183-197.

World Bank (2000): Bangladesh: Climate Change and Sustainable Development, Bangladesh Report No. 21104-BD, Rural Development Unit, South Asia Region, Document of the World Bank.

World Bank (2006): Bangladesh Country Water Resources Assistance Strategy, Report No. 32312-BD, Environment and Social Development Unit, Agriculture and Rural Development Unit, Energy and Infrastructure Unit, South Asia Region, Document of the World Bank.

Part 2

Modelling, Monitoring and Assessment Techniques

7

Modelling Current and Future Pan-European Irrigation Water Demands and Their Impact on Water Resources

Tim Aus der Beek[1], Ellen Kynast[2] and Martina Flörke[2]
[1]*Department of Geography, Heidelberg University*
[2]*Center for Environmental Systems Research, University of Kassel*
Germany

1. Introduction

70% of the gross global water abstractions from water resources can be explained by water withdrawals for irrigation purposes (Portmann et al., 2010). This number even rises to 90% when considering the global water consumption (Siebert et al., 2010), which is also called net irrigation water use. Furthermore, the need of irrigating field crops highly correlates with climatic conditions, which leads to intense irrigation applications in warm and water scarce regions. In pan-Europe this especially holds true for the semi-arid regions in Mediterranean countries, such as in Spain, Israel, and Turkey (Aus der Beek et al., 2010). Therefore, it is important to analyze the impact of these water withdrawals on existing water resources in order to evaluate the consequences for sustainable water management.

Within this model experiment first the historic and current net and gross irrigation water requirements are being spatially explicitly calculated for pan-Europe. The next step includes integrating these irrigation water uses in a hydrological model on the same spatial and temporal domain. After the successful validation and verification of the model results, both for irrigation and hydrology, by comparing them to reported national irrigation sums and observed river runoff data, the model concept is being transferred to simulate potential future changes of and global change impacts on irrigation water use for the 2050s. Hereby, the effects of climate change and socio-economic change on future irrigation withdrawals and water resources are being evaluated separately. Socio-economic impacts on irrigation water withdrawals are mainly being expressed by increasing or decreasing spatial irrigated extents. Here, several factors, amongst others increases in food demand due to increasing world population (Lutz et al., 2008), changing human dietaries (Hanjra & Qureshi, 2010), biofuel production (Timilsina & Shresta, 2011), influence these future irrigated extents. Another important factor is climate change (Schlenker & Lobell, 2010; Olesen & Bindi, 2002), as it not only is able to reduce local yields due increasing air temperature and climate variability but also to increase local yields due to high atmospheric CO2-concentrations (Long et al., 2006). Schaldach et al., (2011a) provide for the first time a separation of these influencing factors on future changes in irrigated areas and irrigation volumes for pan-Europe. In the here conducted study the same model set-up has been used to further analyze the impact of these factors not only on irrigation volumes but also on the consequences for pan-European water resources.

2. Material and methods

2.1 The study region

The pan-European study region has been developed within the EU-FP6 project SCENES which provides different pathways for the future of pan-European freshwater resources. It includes all European countries as well as their neighboring states, reaching from Northern Africa in South to the Near East in the South-East to the Russian Ural Mountains in the East (see Figure 1). The southern and eastern borders of the study region have been derived from river basin boundaries and are thus not concordant with political borders. An overview about the design of the study region and the contents of the SCENES project is given in Kamari et al., (2008). Based on the UN-classification the pan-European study region has been further divided into seven sub-regions to better allow for the analysis of regional differences: NA (Northern Africa), WE (Western Europe), NE (Northern Europe), SE (Southern Europe), EEc (Eastern Europe, central), EEe (Eastern Europe, eastern), and WA (Western Asia).

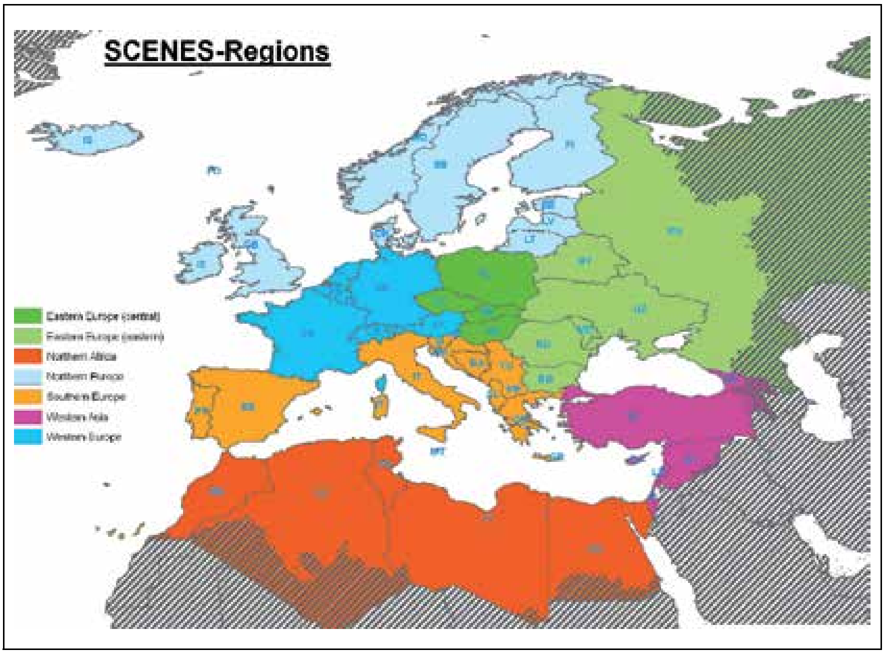


Fig. 1. Spatial extent of the study area and SCENES-regions.

2.2 The WaterGAP3 model

Within this integrated model study the well tested hydrology and water use model WaterGAP3 (Alcamo et al., 2003; Flörke and Alcamo, 2004; Verzano, 2009) is being applied to calculate irrigation water abstractions and their impact on pan-European water resources on a five arc minute grid (~6x9 km per grid cell). All irrigation and hydrology model runs are being conducted for the time period 1961 to 1990 (baseline) and 2041 to 2070 (scenarios 2050s). The calculation of future changes in irrigated areas based on socio-economic drivers (see chapter 2.3) is being conducted by the land use model LandSHIFT (Schaldach et al., 2011b) on the same grid. A detailed overview about the LandSHIFT model and the coupling procedure of LandSHIFT and WaterGAP within this study is given in Schaldach et al., (2011a).

First of all, based on expected population dynamics, food demand, etc. the crop-specific irrigated area maps are being generated by the LandSHIFT model and then fed into the irrigation module of WaterGAP3. The irrigation model then calculates net and gross irrigation demands as described is Aus der Beek et al., (2011):

The start day of the growing season is being calculated for each grid cell separately. For each grid cell the most suitable 150-day period within a year is ranked based on crop specific precipitation and air temperature criteria as given in Allen et al., (1998). The temperature criterion ensures continuous energy supply and optimal growing conditions, whereas the precipitation criterion promotes water supply and prevents cropping periods during droughts. If a day fulfils one of the two criteria, one ranking point is given. The growing season is then defined to be the most highly ranked 150-day period; in case of two consecutive growing periods the combination with the highest total number of ranking points is chosen (Döll & Siebert, 2002). If a second 150-day growing period is suitable, based on the crop specific precipitation and air temperature criteria, then a second cropping period within one year is added to the first period. However, in the current model set up it is not possible to change the crop type for the second period, as the crop-specific land use map provided by LandSHIFT only contains one crop type per grid cell. Therefore, double cropping is always being conducted with the same crop type, which holds true only for some crops in pan-Europe. Furthermore, the assumption of a growing period of 150 days is reasonable for crops such as vegetables, potatoes, pulses, wheat, barley, maize, rice and fruits, but underestimated for fibres and winter wheat, and overestimated for fodder plants (Smith, 1992).

Finally, the net irrigation requirements for each grid cell are being calculated, which are based on the CROPWAT approach published by Smith, (1992):

$$I_{net} = k_c * E_{pot} - P_{eff} \qquad \text{if } E_{pot} > P_{eff}$$

$$I_{net} = 0 \qquad \text{if } E_{pot} \leq P_{eff} \tag{1}$$

with

I_{net} = net irrigation requirement per unit area [mm/d]
P_{eff} = effective precipitation [mm/d]
E_{pot} = potential evapotranspiration [mm/d]
k_c = crop coefficient [-]

Aus der Beek et al., (2011) state further: Within the WaterGAP hydrology and water use modelling framework E_{pot} is consistently being calculated accordingly to Priestley & Taylor, (1972) as a function of air temperature and net radiation (Weiß & Menzel, 2008). K_C values feature a crop specific distinctive distribution curve throughout the growing period and are closely related to LAI development (Liu & Kang, 2007), as they mimic plant development. Each crop has three to four different development stages during its 150-day growing period: nursery (rice only), crop development, mid-season, and late-season.

Finally, the calculation of gross irrigation requirements I_{gr} for each grid cell is being conducted by taking into account net irrigation requirements I_{net} and national irrigation project efficiencies EF_{proj} (Rohwer et al., 2006):

$$I_{gr} = \frac{I_{net}}{EF_{proj}} \tag{2}$$

Irrigation project efficiency reflects the state of irrigation technology within each country. It is also more applicable than the often used irrigation field efficiency as it additionally considers conveyance losses, field sizes and management practices, while irrigation field efficiency mainly results from the irrigation practice (e.g. surface, sprinkler, micro irrigation). EF_{proj} typically ranges between 0.3 and 0.8, whereas 0.8 means that 80% of the water delivered to the crop is actually absorbed by it. Future changes in irrigation efficiency, have been derived by stakeholder meetings within the European research project SCENES. An overview of the performance of the WaterGAP3 irrigation module can be found in Aus der Beek et al., (2010), where its output has been compared to simulated gross irrigation requirements from a vegetation model and to reported values for all pan-European countries on a national basis.

Then, the calculated temporal and spatial explicit data sets on net irrigation requirements are being integrated in the hydrological module of WaterGAP3 (Alcamo et al., 2003; Döll et al., 2003) to assess the impact of irrigation on pan-European water resources. Here, within each irrigated grid cell they are abstracted from the internal water fluxes, and can thus alter river runoff. Also, by relating the amount of water which is being withdrawn for irrigation purposes to the amount of water that is naturally available on grid cell or river basin level, we are able to determine local water stress factors and the sustainability impact of the withdrawals. Furthermore, as WaterGAP3 also computes water withdrawals from other sectors, such as households, manufacturing industries, electricity production (Flörke et al., 2011), and livestock, we can provide an overview of locally dominant water use sectors in pan-Europe and their competition.

2.3 The scenarios

2.3.1 Socio-economic change

The SCENES project provides four different narrative socio-economic scenarios from which two opposing scenarios have been selected for this study, one reference scenario (Economy First) and one policy scenario (Sustainability Eventually). The aim of the scenarios is to provide a basis for the mid- to long-term development planning of pan-European freshwater resources. All scenarios have been designed by applying the story-and-simulation methodology (Alcamo, 2008) which iteratively links storyline revision with modeling exercises. The qualitative drivers for the scenarios have been developed in participatory international panel meetings and consider also environmental factors. The quantitative, i.e. numerical, drivers have been derived from modeling results, which are also influenced by the qualitative drivers, e.g. questionnaires filled out by panel participants (Schaldach et al., 2011a). Therefore, both scenarios offer a consistent set of environmental and socio-economic assumptions for the 2050s, which serve as a basis to study the potential future pathways of irrigation and hydrological developments in our analysis. Here, agricultural development, i.e. irrigated crop production and the impact of technological change, are the most important drivers. The two selected scenarios have been described by Schaldach et al., (2011a) as follows:

- *"Economy First"* (EcF): The economy develops towards globalisation and liberalisation, so innovations spread but income inequality, immigration and urban sprawl cause social tensions. Global demand for food and bio-fuels drives the intensification of agriculture. As the Common Agricultural Policy (CAP) is weakened, farms are abandoned where crop production is uneconomic. Until 2050 technological change allows potential increases of crop yields by 23% within the countries of the European Union (EEc, NE, WE, SE). Countries located in the other regions (EEe, NA, WA) only achieve a 14% potential increase. Total crop production is growing by 29% (from 981.890 kt to 1.266.157 kt). NA has the largest increase (+155%) followed by WA (+88%) and NE (+20%). Only for EEc a decrease of crop production by -4% is assumed. Future trends in population and economic activity show a further increase of population by 32.5% (348 million people) for pan-Europe until 2050. Here, highest growth rates are expected in NA and WA while the population increase in Europe is rather moderate. Economic activity continues to grow over the whole scenario period resulting in an 86% growth in GDP.
- *"Sustainability Eventually"* (SuE): Europe transforms from a globalised, market-oriented to an environmentally sustainable society, where local initiatives are leading. Landscape is the basic unit and there is a strong focus on quality of life. Direct agriculture subsidies are phased out and replaced by policies aimed at environmental services by farmers, such as support for farmers in less favourable areas with high-nature value farmland and accompanied by effective spatial decentralisation policies. Land use changes in general promote greater biological diversity. Crop yields are assumed to potentially increase by 50% until 2050 in all regions. Total crop production is increasing by 6.9 % (from 981.890 kt to 1.049.608 kt) with large regional differences. While crop production is doubling in NA, there is a decrease of --21% in EEe. Population is expected to increase by 13% (143 million people) in pan-Europe between 2000 and 2050. For Europe, a decrease in population is projected whereas for NA and WA the population continues to grow. Compared to EcF, SuE shows a lower total GDP development indicated by developing slower with an increase of 14% between 2000 and 2050.

2.3.2 Climate change

Both climate change scenarios are based on the A2 emission scenario of the IPCC SRES 4th assessment report and are combined in this study with both socio-economic scenarios. Within the A2 scenario the atmospheric CO2-concentration rises up to 492 ppm (IPCC, 2007). In order to include the variability of climate models, which are being employed to calculate climate data sets with the input from the IPCC SRES report, climate output for the A2 scenario from two diverging General Circulation Models (GCMs) have been selected for this study.

The MIMR GCM output has been provided by the MICRO3.2 model at the Center for Climate System Research at the University of Tokio, Japan. Here, the A2 scenario projects high air temperature increases over Europe in combination with low precipitation decreases to high precipitation increases. The MIMR climate data set can be considered as the "wetter" scenario of the two GCMs.

The IPCM4 GCM output has been generated by the IPSL-CM4 model at the Institute Pierre Simon Laplace in France. Here, the A2 scenario indicates higher air temperature increases for Europe than the MIMR GCM and only small changes in precipitation patterns. Thus, within this study the IPCM4 climate data set can be regarded the "dry" scenario of the two GCMs.

The GCM outputs have been downscaled from the original resolution of a T63 grid (1.875°x1.875°) to the 5′ grid of the WaterGAP3 model by applying a bilinear interpolation algorithm. Furthermore, the delta change approach (Henrichs & Kaspar, 2001) has been applied to scale the GCM model output with the observed climate data for the climate normal period (1961 – 1990) from CRU (see chapter 2.2) to include climate variability in this analysis.

3. Results and discussion

3.1 Irrigation

As this study focuses on the impact of irrigation on available water resources, we refer to Schaldach et al., (2011a) for a detailed description of changes in land use patterns and irrigated area extents.

A spatial overview of mean annual pan-European net irrigation water requirements for the baseline period is given in Figure 2. The water demand is highest in the Mediterranean countries, especially in Turkey, Spain, and Italy, which account with 92040 km^2 for about 55% of the total real irrigated area in Europe (Aus der Beek et al., 2010). Also, the riparian zones of the Nile River as well as its Delta are heavily irrigated, both in area and quantity, which can be explained by the concurring semi-arid to arid climate conditions and population pressures. The quantitative summary for each region is given in Table 1. As explained earlier the regions surrounding the Mediterranean Sea features the highest demands: Southern Europe (16.15 bil m^3), Northern Africa (15.6 bil m^3), Western Asia (13.44 bil m^3), followed by Eastern Europe, eastern (5.47 bil m^3), Western Europe (2.38 bil m^3), Northern Europe (0.47 bil m^3), and Eastern Europe, central (0.36 bil m^3). A country based evaluation of the goodness of these model results is given in Aus der Beek et al., (2010), who show that the deviation between modelled and reported irrigation requirements for Europe is about 1%.

Table 1 also summarizes the mean net irrigation requirements for the eight scenario model runs conducted within this study (see Chapter 2.3). The first two scenario model runs have been driven with the A2 model output from two GCMs, IPCM4 and MIMR. The socio-economic drivers, here summarized as land use, have remained in baseline conditions in order to solely analyze the impact of climate change on net irrigation water demands. Both scenarios lead to a small decrease in water demand (-1% and -5%), which is unexpected, as increasing air temperatures naturally cause an increase in evapotranspiration for most crops. Here, the decrease in irrigation water demands originates from the model structure which features a dynamic cell-specific cropping calendar. Based on the climate conditions of each modelled year the most suitable 150 day growing period, and thus the sowing day, is chosen. Therefore, changing climatic conditions shift the sowing dates to earlier or later periods to avoid high irrigation demands in July and August. A more detailed description as well as a graphic example for the Iberian Peninsula of this model algorithm can be found in Schaldach et al., (2011a). In general, this algorithm has rightly been implemented to mimic sowing date decisions from local farmers who would in reality also adapt to changing conditions in order to save expenses for irrigation water and also receive high yields. A model control run with sowing dates from the baseline for the IPCM4 scenario has shown that without these adaptation measures, the net irrigation demand increase by 15% to 61.85 bil m^3 instead of decreasing by 1%. An overview of the spatial distribution of all eight scenario model runs is given in Figure 3.

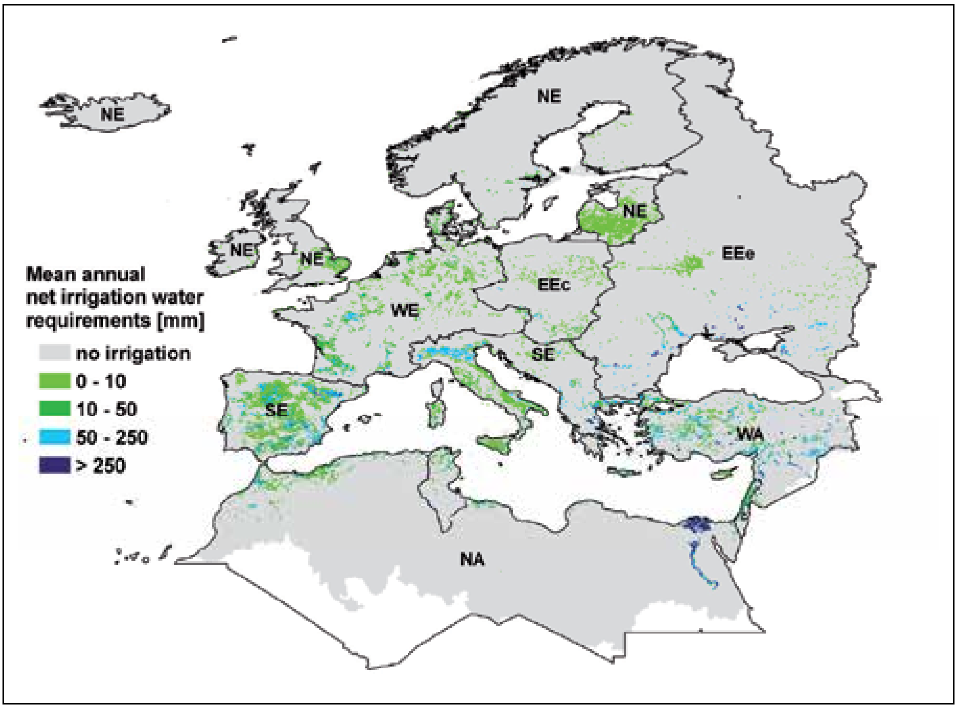


Fig. 2. Mean annual net irrigation requirements in [mm] for the baseline period (1961-90) as modeled with WaterGAP3 (EEc = Eastern Europe central, EEe = Eastern Europe east, NA = Northern Africa, NE = Northern Europe, SE = Southern Europe, WE = Western Europe, WA = Western Asia).

The next two scenario model runs have been conducted with climate input from the baseline but different socio-economic drivers, i.e. the opposing Economy First (EcF) and Sustainability Eventually (SuE) scenarios. Here, the model results show a completely different picture. Both scenarios imply an increase in net irrigation water demand, the optimistic SuE scenarios projects a minor increase of 2% for the 2050s whereas the pessimistic EcF scenario expects an increase of 48%. The differences in the spatial allocation of the water demand are also depicted in Figure 3a and 3b. Especially, in Southern Europe, namely Spain and Italy the opposing trends are evident which is also supported by Table 1 where under EcF conditions an increase of 51% and under SuE conditions an decrease of 11% occurs.

The last four scenario model runs have been conducted as combinations of the climate and socio-economic model drivers. Once again the socio-economic drivers dominate the future potential changes in irrigation water requirements. Under both "optimistic" SuE scenario model runs water demands are stable or decreasing, whereas under both "wetter" climate MIMR scenario model runs the trends are not consistent (-7% vs. +25%). As expected, the highest increase in irrigation water requirements can be observed when combing the "dry" IPCM4 scenario with the "pessimistic" Economy first scenario (+45%).

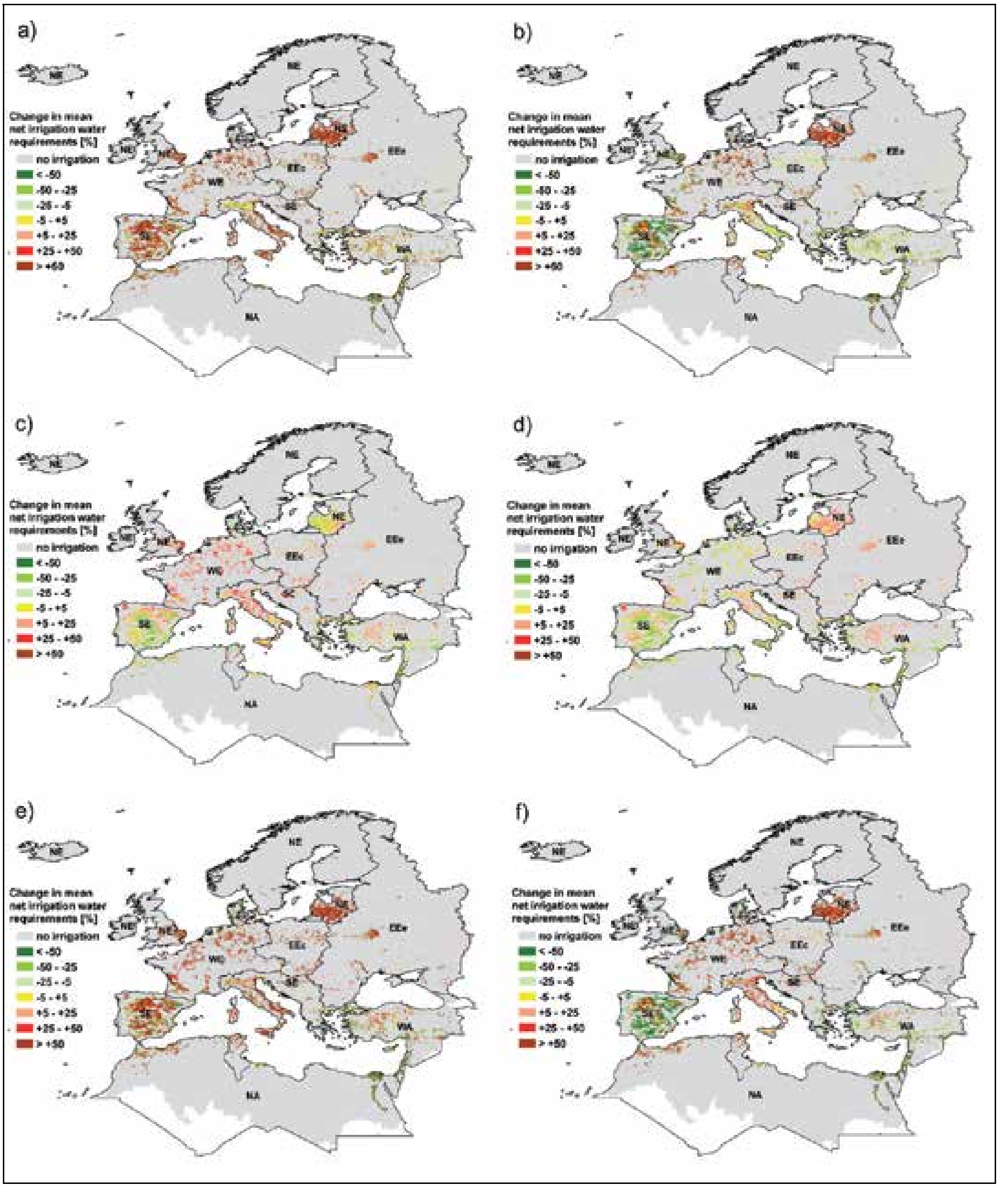
Climate forcing	**Base 61-90**	**IPCM4 2050**	**MIMR 2050**	**Base 61-90**	**Base 61-90**	**IPCM42050**	**IPCM4 2050**	**MIMR 2050**	**MIMR 2050**
Land use	**Base 2000**	**Base 2000**	**Base 2000**	**EcF 2050**	**SuE 2050**	**EcF 2050**	**SuE 2050**	**EcF 2050**	**SuE 2050**
Eastern Europe (central)	0.36	0.43 (+21)	0.41 (+13)	0.72 (+101)	0.40 (+12)	0.88 (+145)	0.49 (+37)	1.04 (+188)	0.56 (+57)
Eastern Europe (eastern)	5.47	5.93 (+8)	5.91 (+8)	7.39 (+35)	3.81 (-30)	8.12 (+49)	4.20 (-23)	7.32 (+34)	3.77 (-31)
Northern Africa	15.60	15.17 (-3)	14.35 (-8)	21.01 (+35)	19.48 (+25)	19.63 (+26)	18.41 (+18)	18.64 (+19)	17.40 (+12)
Northern Europe	0.47	0.49 (+5)	0.46 (-2)	1.20 (+157)	0.46 (-2)	1.34 (+187)	0.51 (+8)	1.09 (+134)	0.40 (-15)
Southern Europe	16.15	15.68 (-3)	14.90 (-8)	24.35 (+51)	14.43 (-11)	22.77 (+41)	13.97 (-14)	14.91 (-8)	11.49 (-29)
Western Asia	13.44	12.59 (-6)	12.83 (-9)	16.79 (+25)	12.50 (-7)	15.53 (+16)	11.66 (-13)	15.40 (+15)	11.53 (-14)
Western Europe	2.38	2.77 (+16)	2.37 (-0)	8.42 (+253)	4.03 (+69)	9.79 (+311)	4.69 (+97)	8.67 (+264)	4.82 (+103)
SUM	53.87	53.06 (-1)	51.23 (-5)	79.87 (+48)	55.11 (+2)	78.06 (+45)	53.92 (+0)	67.08 (+25)	49.98 (-7)

Table 1. Modeled mean net irrigation water requirements in billion m^3 under the IPCC-SRES scenario A2 with two GCMs (IPCM4 and MIMR) for 2040 – 2069 and two socio-economic land-use scenarios (Economy First (EcF) and Sustainability Eventually (SuE)). Numbers in parenthesis describe relative changes compared to the baseline (1961 – 1990), expressed in percent.

However, as the decreasing influence of the climate drivers also lowers the combined water demand due to the adaptive sowing date, it does not top the model run with baseline climate drivers and the EcF scenario (+48%), which can be regarded the worst case scenario. A graphic overview of the combined model run outputs is given in Figure 3e to 3h.

3.2 Hydrological impacts

Within this study the focus has been set on modelling irrigation water withdrawals and their impact on pan-European water resources. However, in order to reach this goal we also need to analyze and quantify the competition of the irrigation water use sector with other sectors. As WaterGAP3 is a state-of-the-art model it additionally considers the other water use sectors: households, electricity generation, and manufacturing industries (see Chapter 2.2). Thus, we have calculated all sectoral water uses on river basin level and ranked their impact for each basin separately. Figure 4 features a pan-European map with dominant water use sectors, where several trends are evident. In the majority of North European river basins the manufacturing sector, e.g. in Scandinavia, and the domestic sector, e.g. in the United Kingdom and Iceland, dominate the water uses. Only Denmark is an exception, as irrigation heads the ranking here. Western and Eastern Europe feature the electricity generation sector as the most used water sector. Southern Europe, Northern Africa, and Western Asia show the irrigation sector to be the most important water use sector due to unfavourable climatic conditions and high population pressures. The patchy composition of water use sectors in Northern Africa, i.e. Libya and Algeria, originates from the location of irrigable areas.



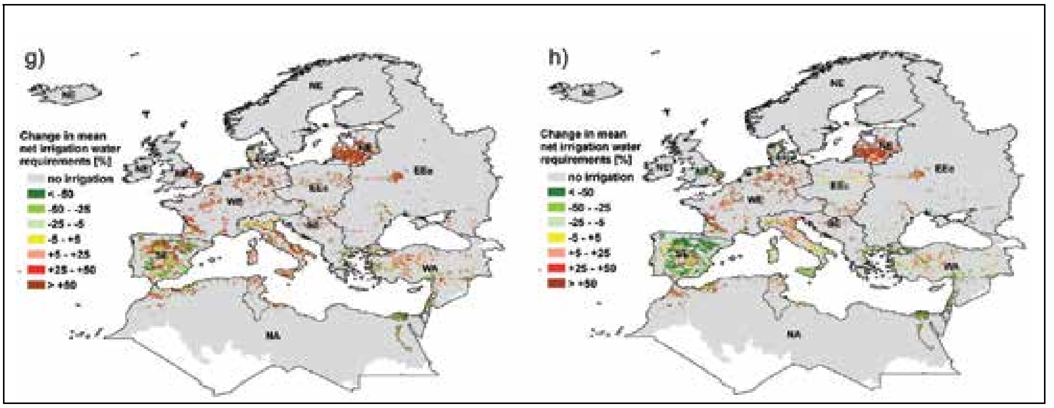


Fig. 3. Change in mean annual net irrigation requirements for the 2050s compared to baseline (1961 -1990) for different combinations of climate (CLIM: baseline; IPCM4; MIMR) and agricultural (AG: baseline; Economy First; Sustainability Eventually) scenarios. a) CLIM: baseline, AG: EcF; b) CLIM: baseline, AG: SuE; c) CLIM: IPCM4, AG: baseline; d) CLIM: MIMR, AG: baseline; e) CLIM: IPCM4, AG: EcF; f) CLIM: IPCM4, AG: SuE; g) CLIM: MIMR, AG: EcF; h) CLIM: MIMR, AG: SuE.

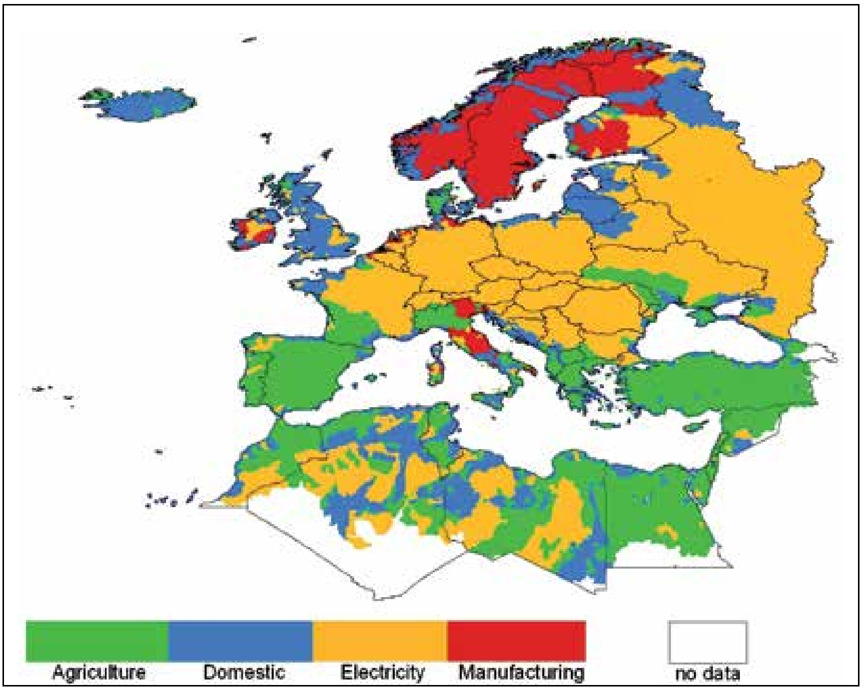
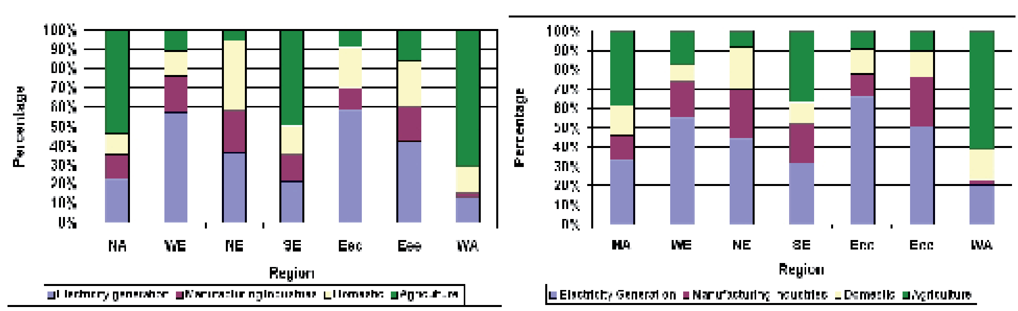


Fig. 4. Most dominant type of water use for the year 2005 on river basin level as modeled with WaterGAP3 for pan-Europe.

It needs to be mentioned that Figure 4 is an example for the year 2005. As our modelling runs are starting in 1961, the spatial as well as numerical patterns are changing within the modelling period. These patterns are influenced by a multifold of model drivers, such as climate, population numbers and allocation, power plant types and location, gross domestic product, etc., which all change with time.

To analyze the importance of irrigation water abstractions for current but also for future conditions we have summarized the shares of all water use sectors on a regional basis. The results for the year 2005 as well as exemplarily for one scenario combination are shown in Figure 5. The description of the spatial distribution of dominant water use sectors, as explained above for Figure 4, is well depicted in Figure 5a. Western Asia, Southern Europe, and Northern Africa feature with about 50% to 70% the largest irrigation water use share, followed by water used for electricity generation. Western and Eastern Europe use about 40% to 60% of their total water withdrawals for electricity generation, followed by households and manufacturing industries. Northern Europe features with about 35% equal shares for households and electricity generation. The results for the 2050s scenario driven with output from the IPCM4 climate model and socio-economic data from the Economy First set, is given in Figure 5b. Here, irrigation water withdrawals in the Mediterranean countries decrease from 50-70% in 2005 to 35-60%, whereas they remain stable or even slightly increase in the other pan-European regions. As climate change does not significantly affect future irrigation water requirements due to the adaptation measures (see Chapter 3.1), the decrease can be derived from two main factors. Firstly, the technical development of irrigation machinery has led to an improvement of the net-to-gross irrigation efficiency ratio (see Equation 2 in Chapter 2.2), reducing irrigation water withdrawals. For example, in Greece the efficiency increased from 0.57 to 0.65 and in Italy from 0.72 to 0.8. Secondly, population numbers for this scenario are decreasing in pan-Europe, except for Northern Africa and Western Asia. This trend is also well shown in Figure 5a and 5b, as water use shares in the household sector are consistently decreasing in mainland Europe. In all pan-European regions the electricity generation water use sector gains shares or its share remains constant, as for example in Western Europe. Similar patterns can be observed for the manufacturing industries water use sector.



a) b)

Fig. 5. Relative share of different water use sectors for pan-European regions as modeled with WaterGAP3: a) year 2005; b) scenario 2050s Economy First/IPCM4 (Eec = Eastern Europe central, Eee = Eastern Europe east, NA = Northern Africa, NE = Northern Europe, SE = Southern Europe, WE = Western Europe, WA = Western Asia).

The next step in this study is the assessment of the impacts of the irrigation water withdrawals explained above on pan-European water resources. Therefore, we have analyzed for all pan-European river basins how irrigation water abstractions affect water stress. As especially during summer time the irrigation water demand is highest, and an annual average stress indicator would mask seasonal streamflow variability, we have analyzed summer water stress induced by irrigation water abstractions, which is displayed in Figure 6. The irrigation WTA (withdrawal-to-availability ratio) indicator is a simple but effective tool to analyze water stress (Cosgrove & Rijsberman, 2000) as it divides irrigation water withdrawals by water availability on river basin level. If less than 20% of the available water resources in a river basin are being exploited, the status of this basin can be defined as low water stress and the abstractions in terms of water quantity can considered as sustainable. Medium water stress is occurring when WTA is between 20% and 40%. If more than 40% of the available water resources within a river basin are being abstracted from the system, the basin endures high water stress and the withdrawals can be considered as unsustainable. A high WTA also affects ecosystem services as environmental flow thresholds, which ensure water limits for flora and fauna, are often not being abode. Figure 6 shows the mean summer irrigation WTA for baseline conditions as well as for the two opposing scenarios combinations IPCM4/Economy Firs and MIMR/ Sustainability Eventually. The baseline results feature high irrigation induced summer water stress in Spain, Turkey, Israel, Greece, Morocco, Libya, and Algeria. Medium stressed river basins are located in Italy (e.g. Po River basin), France, and Morocco. Generally, these countries can be divided into two classes. First, semi-arid to arid regions which suffer low water availability due to climatic conditions, where already small water abstractions drastically increase water stress and water scarcity, as for example in Northern Africa and Western Asia. Secondly, semi-arid to humid regions which overexploit existing water resources, e.g. in Spain and Italy.

The “pessimistic” scenario combination IPCM4/Economy First for the 2050s increase irrigation induced summer water stress in several regions in pan-Europe (see Figure 6b). Here, most parts of France endure high water stress, except for the Rhone River basin, which experiences medium water stress. Also, in the Dniester River basin in the Ukraine water stress increases, as well as in Morocco, Algeria, Portugal, Italy, Germany, Sweden, and the United Kingdom.

The “optimistic” scenario combination MIMR/Sustainability Eventually yields an indifferent picture of pan-European summer water stress (see Figure 6c). In some river basins the water stress level decreases, as for example in Spain, Italy, and Ukraine, whereas other basins experience an increase in water stress, for example in France and Morocco. The reasons for these changes can be found in the high spatial variability of the climate change scenario data and the regional differences in the quantification of the model drivers of the socio-economic scenarios.

The next step in this study includes the impact analysis of water withdrawals from all water use sectors on water availability in pan-Europe. Therefore, we have calculated the mean annual water availability for baseline conditions after subtracting water uses, which is displayed in Figure 7a. High water availability of more than 300 mm per year occurs in Northern Europe, in the alpine basins including the Rhine, as well as in the Balkan Mountains. Medium water availability of 100 mm to 300 mm can be observed in Eastern Europe from Poland to Russia, in Spain, as well as in the countries adjacent to the Black Sea. Low water availability of less than 100 mm per year can be found in Northern Africa.

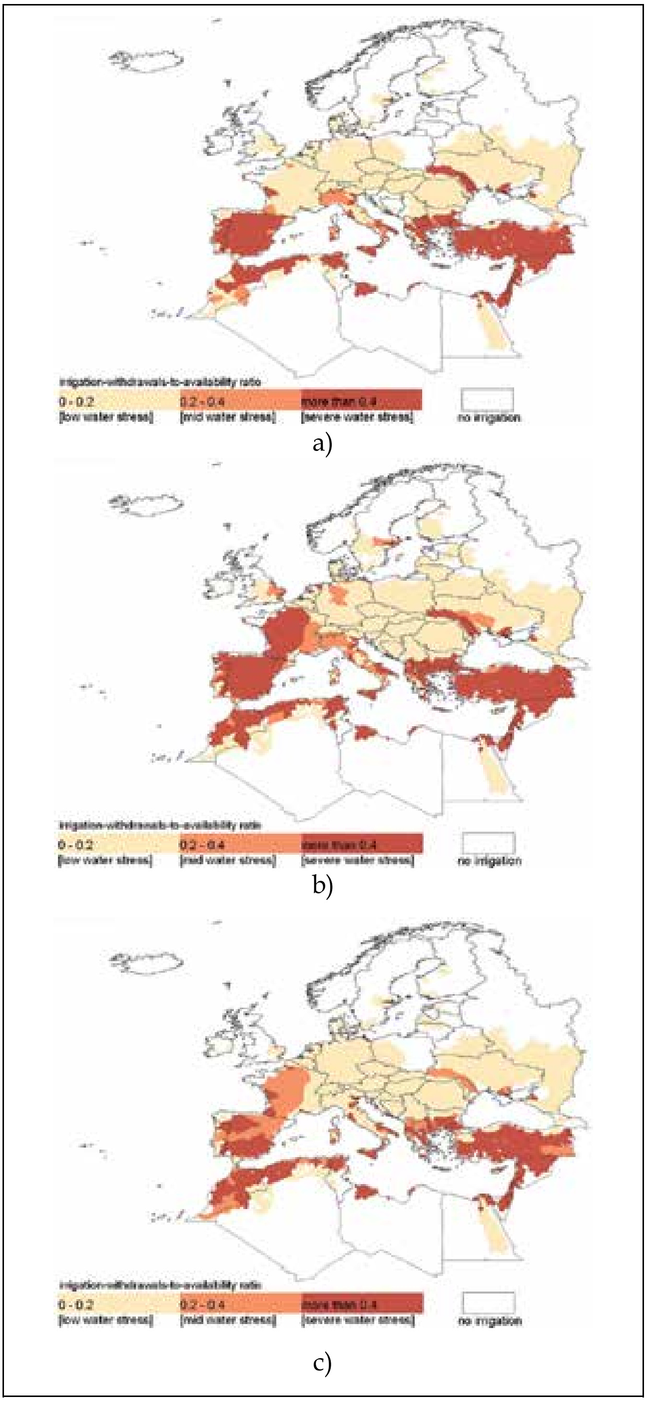


Fig. 6. Irrigation water stress in summer on river basin level for pan-Europe as modeled with WaterGAP3: a) baseline; b) scenario IPCM4/Economy First; c) scenario MIMR/Sustainability Eventually.

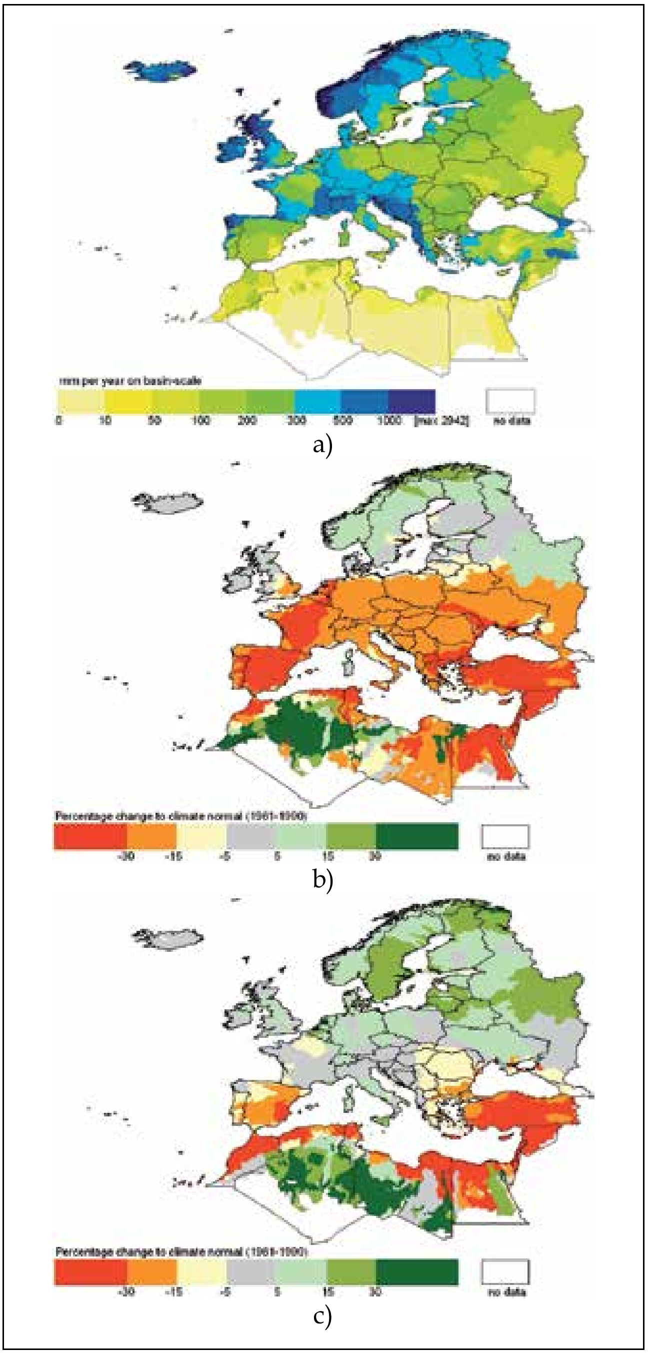


Fig. 7. a) Mean annual water availability for the baseline on river basin level for pan-Europe as modeled with WaterGAP3 with water uses; Relative change of mean annual water availability for the 2050s: b) scenario IPCM4/Economy First; c) scenario MIMR/Sustainability Eventually.

Figure 7b depicts the relative changes in water availability under the "pessimistic" IPCM4/Economy First scenario combination. High decreases of more than 30% can be observed in large parts of Spain, France, Turkey, and Israel, which is concordant with the findings of the irrigation induced summer water stress analysis (see Figure 6b). This leads to the conclusion, which is also supported by the data analysis that large parts of these decreases can be ascribed to irrigation water uses. Decreases of 15% to 30% are occurring in Central und Eastern Europe, whereas large parts of Northern Europe feature increases of 5% to 30%. The patchy patterns in Northern Africa can be explained with generally low water availabilities in the region, leading to large positive and negative changes in local water availabilities.

Figure 7c depicts the relative changes in water availability under the "optimistic" MIMR/Sustainability Eventually scenario combination. Here, decreases larger than 15% only occur in Western Asia, Northern Africa, and Spain. Also, in contrast to the pessimistic scenario described above, Central and Eastern Europe, except for Hungary, feature stable to increasing trends in water availability.

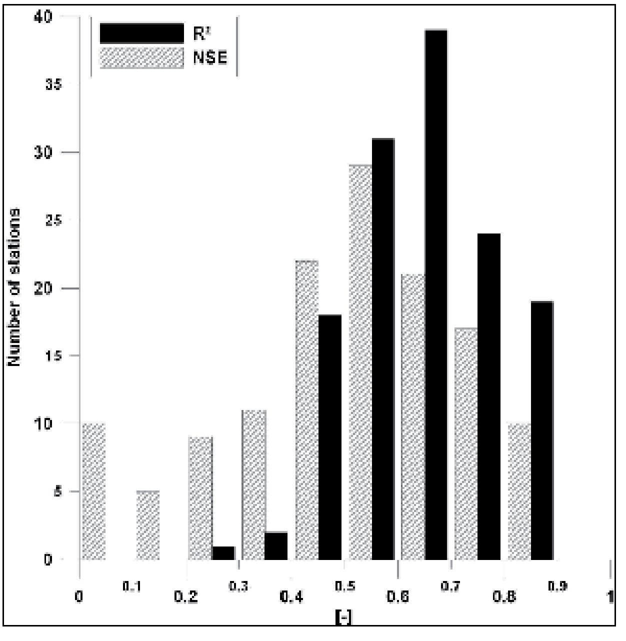


Fig. 8. Evaluation of the WaterGAP3 model performance: comparison of modelled and observed river runoff for 134 gauging stations in pan-Europe (R^2: coefficient of determination; NSE: Nash-Sutcliffe efficiency).

In order to analyze the performance of the hydrological module of the WaterGAP3 model, and thus the plausibility of the results of this study, we have compared observed to modelled river runoff at all river gauging stations available at Global Runoff Data Center (GRDC, 2004). Totally, runoff data from 152 stations have been available for the pan-European extent and the temporal domain of this study, whereas 18 stations have been deleted due to unrealistic data assumptions and trend tests. The goodness of fit between observed and modelled data has been evaluated by calculating the coefficient of determination R^2 and the Nash-Sutcliffe efficiency NSE (Krause et al., 2005) for each station. A histogram of the distribution of R^2 and NSE is given in Figure 8. Generally, an average R^2 of 0.64 with minimum and maximum values of 0.25 and 0.87 have been calculated. The NSE parameter, which is more sensitive to deviations in peak flows, features an average value of 0.5, whereas minimum and maximum values span a range of 0.01 to 0.86. The sensitivity of NSE is apparent when analyzing Figure 8. 35 stations, which is about 25% of the total station number, have a NSE smaller than 0.4, whereas only 3 stations (2%) feature a R^2 smaller than 0.4. This leads to the conclusion that at these 35 stations the magnitude of peak flows could not be very well represented by WaterGAP3, which is also supported by the visual analysis of the hydrographs. To display the differences in both evaluation criteria we have selected two out of the 134 hydrographs; one where the difference is large (Figure 9a) and one with small differences (Figure 9b). Figure 9a features a hydrograph of the Italian Adige River at the gauging station Trento which has a river basin size of 10049 km². The overestimation of peak flows, for example in summer 1967, as well as the underestimation of base flows, e.g. in winter 1969, leads to a poor NSE criterion of 0.14. However, as timing of peak and base flow is generally well represented by WaterGAP3, and overall volume errors balance out, the R^2 criterion shows a high value of 0.71. The opposite case where both, magnitude and timing of base and peak flows, are synchronic is given in Figure 9b. Here, modelled and observed runoff of the Duero River at the Spanish gauging station Villachica is displayed (basin size: 40513 km²). The high agreement of both data sets is reflected in the high model performance of 0.86 for both criteria, R^2 and NSE.

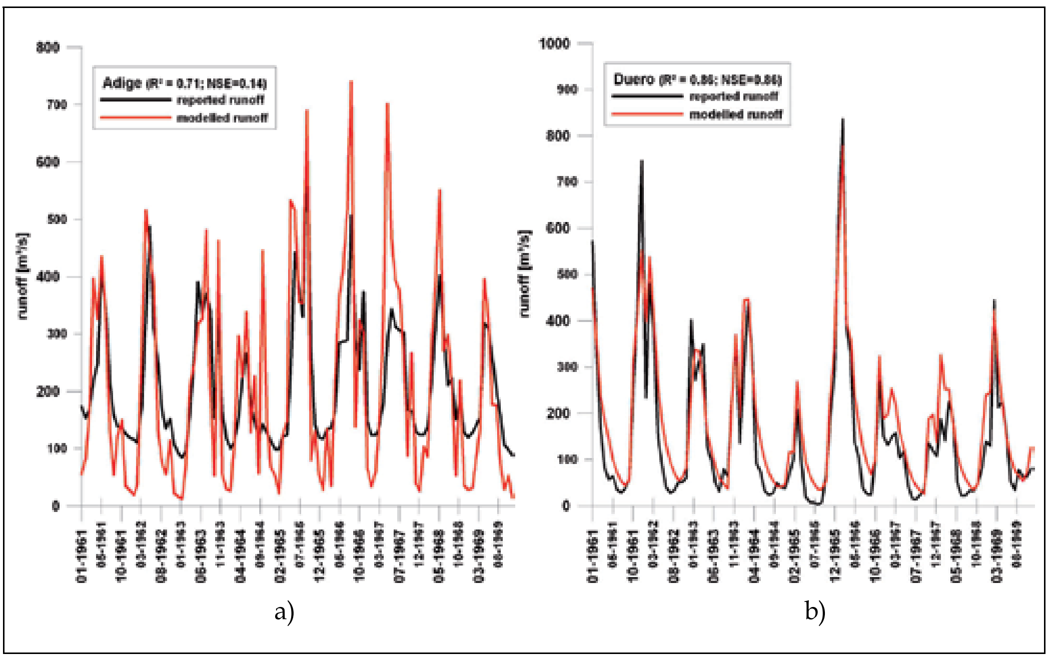


Fig. 9. Observed and modelled river runoff for 1961 to 1970: a) Adige River at station Trento (basin size 10049 km²); b) Duero River at station Villachica (basin size 40513 km²).

An analysis of the performance of the irrigation module in WaterGAP3 has been carried out in Aus der Beek et al. (2010, 2011).

3. Conclusions

Within this study the pan-European irrigation requirements as well as their impact on water resources has been analyzed and quantified by applying the continental hydrology and water use model WaterGAP3. Three regional hot spots of excessive irrigation water use have been identified which are all located in the vicinity of the Mediterranean Sea: Southern Europe, Western Asia, and Northern Africa. For the baseline period 1961 to 1990 about 84% of all pan-European irrigation water withdrawals occur in these three regions. Here, in opposition to the other regions, irrigation is also the dominant water use sector, except for Denmark and parts of the Ukraine. In Western and Eastern Europe water use for electricity generation is the largest sector, whereas it is domestic water use in the United Kingdom, and water use for manufacturing industries in Scandinavia. High unsustainable irrigation water withdrawals, especially in the often semi-arid and water scarce Mediterranean rim countries, lead to summer water stress, as mostly irrigation occurs in the dry and hot summer months. The water-stressed Mediterranean river basins can be separated into two classes: a) generally water scarce basins due to unfavourable climatic conditions, where already small water withdrawals drastically increase water stress (i.e. in Northern Africa and parts of Western Asia); b) overexploitation of water resources in semi-arid to humid regions, where sustainable irrigation applications would be possible (i.e. in large parts of Southern Europe). These model results have successfully been verified by comparing them to observed data, which has proven the plausibility of the methods applied in this study. Thus, it could be considered methodologically sound to transfer the WaterGAP3 model algorithms to calculate future scenarios of irrigation water use and their hydrological impacts. Here, the differentiation between climate change and socio-economic effects on irrigation water use has shown that model drivers such as land use change, due to changes in food demand, feature the largest impact on irrigation and thus hydrological quantities. Especially, as adaptive measures, such as shifts in crop sowing dates due to the elongated vegetation period, are already integrated in this study set-up and have shown to save 15% water for irrigation purposes. Thus, climate change impacts alone have nearly no impacts on future irrigation water requirements in this study. On the other hand, socio-economic impacts span a wide range of potential consequences for future irrigation water use of +2% to +48% for the 2050s. In combination with the smaller, often even slightly negative changes of climate change impacts, this range changes to -7% to +45%. According to the model results the dominance of the irrigation water use sector is also decreasing, as the electricity generation water use sector is gaining shares in the 2050s. In terms of future changes in summer water stress induced by irrigation water use, large differences between the best and worst case scenario can be observed. Here, especially river basins in Western and Southern Europe as well as in Northern Africa are affected, as a multifold of these basins stands at the crossroads of suffering (additional) water stress. Even more apparent differences between both scenarios are the changes in mean annual water availability. Here, Western and Eastern Europe show the most significant range, as water availability can drop by 15% to 30% in the worst case scenario, or can increase up to 15% in the best case scenario.

4. Acknowledgments

The authors would like to thank the Global Runoff Data Center in Koblenz, Germany for providing observed river runoff data for the stations applied in this study. Also, Christof

Schneider has contributed to this publication by generating pan-European maps. This study has been funded by the European Commission project *SCENES*.

5. References

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T. & Siebert, S. (2003). Development and testing of the WaterGAP2 global model of water use and availability; *Hydr. Sc.*, 48 (3): 317-337.

Alcamo, J., 2008. Environmental Futures, 2. *The Practice of Environmental Scenario Analysis*. Elsevier B.V., New York, USA.

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. (1998). *FAO Irrigation and drainage paper 56*: Crop evapotranspiration - Guidelines for computing crop water requirements. FAO - Food and Agriculture Organization of the United Nations, Rome, Italy.

Aus der Beek, T., Flörke, M., Lapola, D.M., Schaldach, R., Voß, F. & Teichert, E. (2010). Modelling historical and current irrigation water demand on the continental scale: Europe. *Advances in Geosciences*, 27: 79-85.

Aus der Beek, T., Voß, F. & Flörke, M. (2011). Modelling the impact of global change on the hydrological system of the Aral Sea basin. *Physics and Chemistry of the Earth*, 36: 684-694.

Cosgrove, W. & Rijsberman, F. (2000). *World Water Vision: Making Water Everybody's Business*. World Water Council, Earthscan Publications, London.

Döll, P. & Siebert S. (2002). Global Modelling of Irrigation Water Requirements. *Water Resources Research*, 38 (4): 8.1-8.10.

Döll, P., Kaspar, F. & Lehner, B. (2003). A global hydrological model for deriving water availability indicators: model tuning and validation. *J. Hydrol.*, Vol. 270, 105-134.

Flörke, M. & Alcamo, J. (2004). *European outlook on water use*. Technical Report prepared for the European Environment Agency. Kongens Nytorv. 6. DK-1050. Copenhagen, DK URL: // http: scenarios.ewindows.eu.org/reports/fol949029

Flörke, M., Bärlund, I. & Teichert, E. (2010). Future changes of freshwater needs in European power plants. *Management of Environmental Quality*. 22(1): 89-104.

GRDC – Global Runoff Data Center (2004). *Long Term Mean Monthly Discharges and Annual Characteristics of selected GRDC Stations*. The Global Runoff Data Center: Koblenz, Germany.

Hanjra, M.A. & Qureshi, M.E. (2010). Global water crisis and future food security in an era of climate change. *Food Policy*, 35: 365–377.

Henrichs, T. & Kaspar, F. (2001). Baseline-A: *A reference scenario of global change*. In: Lehner, B., T. Henrichs, P. Döll, J. Alcamo (Eds.), EuroWasser: Model-based assessment of European water resources and hydrology in the face of global change. Center for Environmental Systems Research, University of Kassel, Kassel World Water Series – Report No. 5: 4.1-4.8.

Intergovernmental Panel on Climate Change (IPCC), Alley, R.B., Allison, I., Carrasco, J., Falto, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R.H. & Zhang, T. (2007). *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the

Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge Univ. Press, Cambridge, U.K.

Kamari, J., Alcamo, J., Barlund, I., Duel, H., Farquharson, F., Florke, M., Fry, M., Houghton-Carr, H., Kabat, P., Kaljonen, M., Kok, K., Meijer, K.S., Rekolainen, S., Sendzimir, J., Varjopuro, R. & Villars, N. (2008). Envisioning the future of water in Europe - the SCENES project. *E-WAter*, 2008: 1-28.

Krause, P., Doyle, D.P & Bäse, F. (2005). Comparison of different efficiency criteria for hydrological model assessment. *Advances in Geosciences*, 5, 89-97.

Liu, H.J. & Kang, Y. (2007). Sprinkler irrigation scheduling of winter wheat in the North China Plain using a 20 cm standard pan. *Irrigation Science*, 25 (2): 149-159.

Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nösberger, J. & Ort, D.R. (2006). Food for Thought: Lower-Than-Expected Crop Yield Stimulation with Rising CO2 Concentrations, *Science*, 312 (5782): 1918-1921.

Lutz, W., Sanderson, W. & Scherbov, S. (2008). The coming acceleration of global population ageing. *Nature* 451: 716-719.

Olesen, J.E. & Bindi, M. (2002). Consequences of climate change for European agricultural productivity, land use and policy. *European Journal of Agronomy*, 16(4): 239-262.

Portmann, F.T., Siebert, S. & Döll, P. (2010). MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*, 24, GB1011.

Priestley, C.H.B. & Taylor, R.J. (1972). On the assessment of surface heat flux and evaporation using large scale parameters. *Monthly Weather Review*, 100: 81-92.

Rohwer, J., Gerten, D. & Lucht, W. (2006). *Development of functional irrigation types for improved global crop modeling*; PIK-Report 106; PIK; Potsdam, Germany.

Schaldach, R., Koch, J., Aus der Beek, T., Kynast, E. & Flörke, M. (2011). Current and future irrigation water requirements in pan-Europe: A comparative analysis of influencing factors. *Global and Planetary Change* (in review).

Schaldach, R., Alcamo, J., Koch, J., Kölking, C., Lapola, D.M., Schüngel, J. & Priess, J.A. (2011b). An integrated approach to modelling land use change on continental and global scales. *Environmental Modelling and Software,* 26 (8): 1041-1051.

Schlenker, W. & Lobell, D.B. (2010). Robust negative impacts of climate change on African agriculture. *Env. Res. Lett.* 5, doi10.1088/1748-9326/5/1/014010.

Siebert, S., Burke, J., Faures, J.M., Frenken, K., Hoogeveen, J., Döll, P. & Portmann, F.T. (2010). Groundwater use for irrigation - a global inventory. *Hydrol. Earth Syst. Sci.*, Vol. 14, 1863-1880, doi:10.5194/hess-14-1863-2010.

Smith, M. (1992). *Irrigation and Drainage Pap. 46,* CROPWAT - A computer program for irrigation planning and management, Food and Agric. Org. of the U. N., Rome, Italy.

Timilsina, G.R. & Shrestha, A. (2011). How much hope should we have for biofuels? *Energy*, Volume 36, Issue 4, Pages 2055-2069.

Verzano, K. (2009). *Climate Change Impacts on Flood Related Hydrological Processes: Further Development and Application of a Global Scale Hydrological Model*. Dissertation University of Kassel, Germany. Available at:

www.mpimet.mpg.de/fileadmin/publikationen/Reports/WEB_BzE_71_verzano.pdf

Weiß, M. & Menzel, L. (2008). A global comparison of four potential evapotranspiration equations and their relevance to stream flow modelling in semi-arid environments. *Adv. Geosci.*,18, 15-23.

8

Basics and Application of Ground-Penetrating Radar as a Tool for Monitoring Irrigation Process

Kazunori Takahashi[1], Jan Igel[1], Holger Preetz[1] and Seiichiro Kuroda[2]
[1]Leibniz Institute for Applied Geophysics
[2]National Institute for Rural Engineering
[1]Germany
[2]Japan

1. Introduction

Ground-penetrating radar (GPR) is a geophysical method that employs an electromagnetic technique. The method transmits and receives radio waves to probe the subsurface. One of the earliest successful applications was measuring ice thickness on polar ice sheets in 1960s (Knödel et al., 2007). Since then, there have been rapid developments in hardware, measurement and analysis techniques, and the method has been extensively used in many applications, such as archaeology, civil engineering, forensics, geology and utilities detection (Daniels, 2004).

There are a variety of methods to measure soil water content. The traditional method is to dry samples from the field and compare the weights of the samples before and after drying. This method can analyse sampled soils in detail and the results may be accurate. A classical instrument for in situ measurements is the tensiometer, which measures soil water tension. These methods have the disadvantages of being destructive and time-intensive, and thus it is impossible to capture rapid temporal changes. Therefore, a number of sophisticated physical methods have been developed for non-destructive in situ measurements. One of these methods is time domain reflectometry (TDR), which has been widely used for determining soil moisture since the 1980s (Topp et al., 1980; Noborio, 2001; Robinson et al., 2003). TDR measurements are easy to carry out and cost effective, however they are not suitable for obtaining the high-resolution soil water distribution because either a large number of probes have to be installed or a single measurement has to be repeated at various locations. In addition, TDR measurements are invasive; the probes must be installed into soil, which may slightly alter the soil properties. GPR has the potential to overcome these problems and is considered one of the most suitable methods for monitoring soil water content during and after irrigation because of the following features:

- The GPR response reflects the dielectric properties of soil that are closely related to its water content.
- GPR data acquisition is fast compared to other geophysical methods. This feature enables measurements to be made quickly and repeatedly, yielding high temporal resolution monitoring. This is very important for capturing rapid changes.

- GPR can be used as a completely non-invasive method. The antennas do not have to touch the ground and thus it does not disturb the natural soil conditions.
- GPR systems are compact and easy to use compared to other geophysical methods. This feature enables scanning over a wide area and the collection of 2D or 3D data. Further, the distribution of soil properties can be obtained with high spatial resolution.

The objective of this chapter is to provide the basics of GPR and examples of its application. Readers who are interested in this measurement technique can find more detailed and useful information in the references listed at the end of the chapter.

2. Basic principles of GPR

A GPR system consists of a few components, as shown in Fig. 1, that emit an electromagnetic wave into the ground and receive the response. If there is a change in electric properties in the ground or if there is an anomaly that has different electric properties than the surrounding media, a part of the electromagnetic wave is reflected back to the receiver. The system scans the ground to collect the data at various locations. Then a GPR profile can be constructed by plotting the amplitude of the received signals as a function of time and position, representing a vertical slice of the subsurface, as shown in Fig. 2. The time axis can be converted to depth by assuming a velocity for the electromagnetic wave in the subsurface soil.

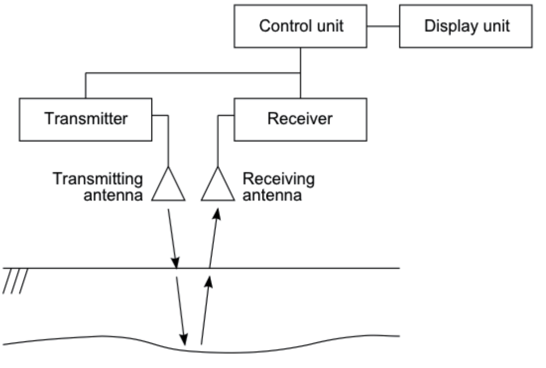


Fig. 1. Block diagram of a GPR system.

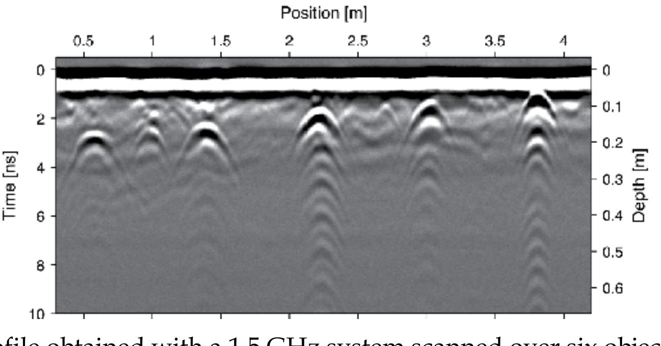


Fig. 2. A GPR profile obtained with a 1.5 GHz system scanned over six objects buried in sandy soil. The signal amplitude is plotted as a function of time (or depth) and position. Relatively small objects are recognised by hyperbolic-shaped reflections. Reflections from the ground surface appear as stripes at the top of the figure.

2.1 Electromagnetic principles of GPR

2.1.1 Electromagnetic wave propagation in soil

The propagation velocity v of the electromagnetic wave in soil is characterised by the dielectric permittivity ε and magnetic permeability μ of the medium:

$$v = \frac{1}{\sqrt{\varepsilon\mu}} = \frac{1}{\sqrt{\varepsilon_0 \varepsilon_r \mu_0 \mu_r}} \tag{1}$$

where ε_0 = 8.854 x 10^{-12} F/m is the permittivity of free space, $\varepsilon_r = \varepsilon/\varepsilon_0$ is the relative permittivity (dielectric constant) of the medium, $\mu_0 = 4\pi$ x 10^{-7} H/m is the free-space magnetic permeability, and $\mu_r = \mu/\mu_0$ is the relative magnetic permeability. In most soils, magnetic properties are negligible, yielding $\mu = \mu_0$, and Eq. 1 becomes

$$v = \frac{c}{\sqrt{\varepsilon_r}} \tag{2}$$

where c = 3 x 10^8 m/s is the speed of light. The wavelength λ is defined as the distance of the wave propagation in one period of oscillation and is obtained by

$$\lambda = \frac{v}{f} = \frac{2\pi}{\omega\sqrt{\varepsilon\mu}} \tag{3}$$

where f is the frequency and $\omega = 2\pi f$ is the angular frequency.

In general, dielectric permittivity ε and electric conductivity σ are complex and can be expressed as

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{4}$$

$$\sigma = \sigma' - j\sigma'' \tag{5}$$

where ε' is the dielectric polarisation term, ε'' represents the energy loss due to the polarisation lag, σ' refers to ohmic conduction, and σ'' is related to faradaic diffusion (Knight & Endres, 2005). A complex effective permittivity expresses the total loss and storage effects of the material as a whole (Cassidy, 2009):

$$\varepsilon^e = \left(\varepsilon' + \frac{\sigma''}{\omega}\right) - j\left(\varepsilon'' + \frac{\sigma'}{\omega}\right) \tag{6}$$

The ratio of the imaginary and real parts of the complex permittivity is defined as tan δ (loss tangent):

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \cong \frac{\sigma'}{\omega\varepsilon'} \tag{7}$$

When ε'' and σ'' are small, it is approximated as the right most expression. In the plane-wave solution of Maxwell's equations, the electric field E of an electromagnetic wave that is travelling in z-direction is expressed as

$$E(z,t) = E_0 e^{j(\omega t - kz)} \tag{8}$$

where E_0 is the peak signal amplitude and $k = \omega\sqrt{\varepsilon\mu}$ is the wavenumber, which is complex if the medium is conductive, and it can be separated into real and imaginary parts:

$$k = \alpha + j\beta \tag{9}$$

The real part α and imaginary part β are called the attenuation constant (Np/m) and phase constant (rad/m), respectively, and given as follows:

$$\alpha = \omega\left[\frac{\varepsilon'\mu}{2}\left(\sqrt{1+\tan^2\delta} - 1\right)\right]^{1/2} \tag{10}$$

$$\beta = \omega\left[\frac{\varepsilon'\mu}{2}\left(\sqrt{1+\tan^2\delta} + 1\right)\right]^{1/2} \tag{11}$$

The attenuation constant can be expressed in dB/m by $\alpha' = 8.686\alpha$. The inverse of the attenuation constant:

$$\delta = \frac{1}{\alpha} \tag{12}$$

is called the skin depth. It gives the depth at which the amplitude of the electric field decay is $1/e$ (~ -8.7 dB, ~ 37%). It is a useful parameter to describe how lossy the medium is. Table 1 provides the typical range of permittivity, conductivity and attenuation of various materials.

Material	Relative permittivity	Conductivity [S/m]	Attenuation constant [dB/m]
Air	1	0	0
Freshwater	81	10^{-6}-10^{-2}	0.01
Clay, dry	2-6	10^{-3}-10^{-1}	10-50
Clay, wet	5-40	10^{-1}-10^{-0}	20-100
Sand, dry	2-6	10^{-7}-10^{-3}	0.01-1
Sand, wet	10-30	10^{-3}-10^{-2}	0.5-5

Table 1. Typical range of dielectric characteristics of various materials measured at 100 MHz (Daniels, 2004; Cassidy, 2009).

2.1.2 Reflection and transmission of waves

GPR methods usually measure reflected or scattered electromagnetic signals from changes in the electric properties of materials. The simplest scenario is a planar boundary between two media with different electric properties as shown in Fig. 3, which can be seen as a layered geologic structure.

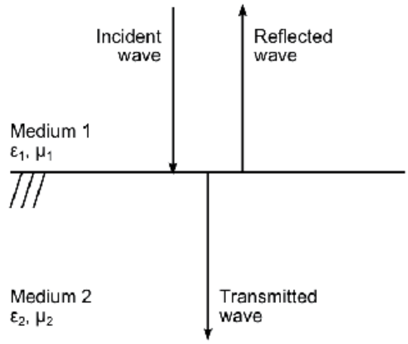


Fig. 3. Reflection and transmission of a normally incident electromagnetic wave to a planar interface between two media.

When electromagnetic waves impinge upon a planar dielectric boundary, some energy is reflected at the boundary and the remainder is transmitted into the second medium. The relationships of the incident, reflected, and transmitted electric field strengths are given by

$$E^i = E^r + E^t \tag{13}$$

$$E^r = R \cdot E^i \tag{14}$$

$$E^t = T \cdot E^i \tag{15}$$

respectively, where R is the reflection coefficient and T is the transmission coefficient. In the case of normal incidence, illustrated in Fig. 3, the reflection and transmission coefficients are given as

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{16}$$

$$T = 1 - R = \frac{2Z_2}{Z_2 + Z_1} \tag{17}$$

where Z_1 and Z_2 are the intrinsic impedances of the first and second media, respectively, and $Z = \sqrt{\mu/\varepsilon}$. In a low-loss non-conducting medium, the reflection coefficient may be simplified as (Daniels, 2004)

$$R \cong \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}} \tag{18}$$

2.2 GPR systems

A GPR system is conceptually simple and consists of four main elements: the transmitting unit, the receiving unit, the control unit and the display unit (Davis & Annan, 1989), as depicted in Fig. 1. The basic type of GPR is a time-domain system in which a transmitter generates pulsed signals and a receiver samples the returned signal over time. Another common type is a frequency-domain system in which sinusoidal waves are transmitted and received while sweeping a given frequency. The time-domain response can be obtained by an inverse Fourier transform of the frequency-domain response.

GPR systems operate over a finite frequency range that is usually selected from 1 MHz to a few GHz, depending on measurement requirements. A higher frequency range gives a narrower pulse, yielding a higher time or depth resolution (i.e., range resolution), as well as lateral resolution. On the other hand, attenuation increases with frequency, therefore high-frequency signal cannot propagate as far and the depth of detection becomes shallower. If a lower frequency is used, GPR can sample deeper, but the resolution is lower.

Antennas are essential components of GPR systems that transmit and receive electromagnetic waves. Various types of antennas are used for GPR systems, but dipole and bowtie antennas are the most common. Most systems use two antennas: one for transmitting and the other for receiving, although they can be packaged together. Some commercial GPR systems employ shielded antennas to avoid reflections from objects in the air. The antenna gain is very important in efficiently emitting and receiving the electromagnetic energy. Antennas with a high gain help improve the signal-to-noise ratio. To achieve a higher antenna gain, the size of an antenna is determined by the operating frequency. A lower operating frequency requires larger antennas. Small antennas make the system compact, but they have a low gain at lower frequencies.

2.3 GPR surveys

GPR surveys can be categorised into reflection and transillumination measurements (Annan, 2009). Reflection measurements commonly employ configurations called common-offset and common midpoint. If antennas are placed on the ground, there are propagation paths both in and above the ground, as shown in Fig. 4. Transillumination measurements are usually carried out using antennas installed into trenches or drilled wells.

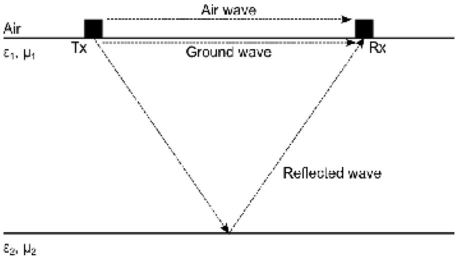


Fig. 4. Propagation paths of electromagnetic waves for a surface GPR survey with a layered structure in the subsurface.

2.3.1 Common-offset (CO) survey

In a common-offset survey, a transmitter and receiver are placed with a fixed spacing. The transmitter and receiver scan the survey area, keeping the spacing constant and acquiring the data at each measurement location, as depicted in Fig. 5. For a single survey line, the acquired GPR data corresponds to a 2D reflectivity map of the subsurface below the scanning line, i.e., a vertical slice (e.g., Fig. 2). By setting multiple parallel lines, 3D data can be obtained and horizontal slices and 3D maps can be constructed.

2.3.2 Common midpoint (CMP) survey

In a common midpoint survey, a separate transmitter and receiver are placed on the ground. The separation between the antennas is varied, keeping the centre position of the antennas constant. With varying separation and assuming a layered subsurface structure, various signal paths with the same point of reflection are obtained and the data can be used to estimate the radar signal velocity distribution versus subsurface depth (e.g., Annan, 2005; Annan, 2009). The schematic configuration of a CMP survey is shown in Fig. 5. When the transmitter is fixed, instead of being moved from the midpoint together with the receiver, and if only the receiver is moved away from the transmitter, the setup is called a wide-angle reflection and refraction (WARR) gather.

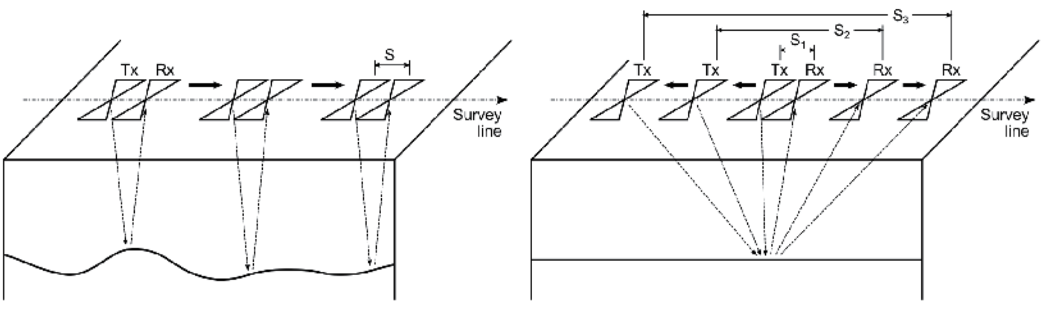


Fig. 5. Schematic illustrations of common-offset (left) and common midpoint (right) surveys. Tx and Rx indicate the transmitting and receiving antennas, respectively. Antennas are scanned with a fixed spacing S in the common-offset configuration, while the spacing is varied as shown with S_1, S_2, S_3 … with respect to the middle position in the common midpoint configuration.

2.3.3 Transillumination measurements

Zero-offset profiling (ZOP) uses a configuration where the transmitter and receiver are moved in two parallel boreholes with a constant distance (Fig. 6, left), resulting in parallel raypaths in the case of homogeneous subsurface media. This setup is a simple and quick way to locate anomalies.

Transillumination multioffset gather surveying provides the basis of tomographic imaging. The survey measures transmission signals through the volume between boreholes with varying angles (Fig. 6, right). Tomographic imaging constructed from the survey data can provide the distribution of dielectric properties of the measured volume.

2.4 Physical properties of soil

As seen in the previous section, the electric and magnetic properties of a medium influence the propagation and reflection of electromagnetic waves. These properties are dielectric permittivity, electric conductivity and magnetic permeability.

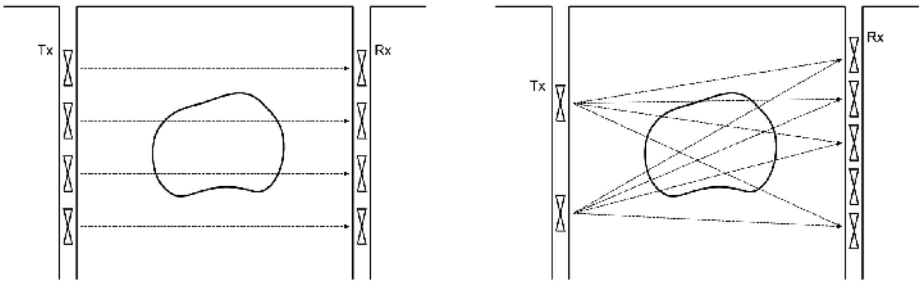


Fig. 6. Schematic illustrations of transillumination zero-offset profiling (left) and transillumination multioffset gather (right) configurations.

2.4.1 Dielectric permittivity

Permittivity describes the ability of a material to store and release electromagnetic energy in the form of electric charge and is classically related to the storage ability of capacitors (Cassidy, 2009). Permittivity greatly influences the electromagnetic wave propagation in terms of velocity, intrinsic impedance and reflectivity. In natural soils, dielectric permittivity might have a larger influence than electric conductivity and magnetic permeability (Lampe & Holliger, 2003; Takahashi et al., 2011).

Soil can be regarded as a three-phase composite with the soil matrix and the pore space that is filled with air and water. The pore water phase of soil can be divided into free water and bound water that is restricted in mobility by absorption to the soil matrix surface. The relative permittivity (dielectric constant) of air is 1, is between 2.7 and 10 for common minerals in soils and rocks (Ulaby et al., 1986), while water has a relative permittivity of 81, depending on the temperature and frequency. Thus, the permittivity of water-bearing soil is strongly influenced by its water content (Robinson et al., 2003). Therefore, by analysing the dielectric permittivity of soil measured or monitored with GPR, the soil water content can be investigated.

As mentioned previously, water plays an important role in determining the dielectric behaviour of soils. The frequency-dependent dielectric permittivity of water affects the permittivity of soil. Within the GPR frequency range, the frequency dependence is caused by polarisation of the dipole water molecule, which leads to relaxation. A simple model describing the relaxation is the Debye model in which the relaxation is associated with a relaxation time τ that is related to the relaxation frequency $f_{relax} = 1/(2\pi\tau)$. From this model, the real component of permittivity ε' and imaginary component ε'' are given by

$$\varepsilon'(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+\omega^2\tau^2} \tag{19}$$

$$\varepsilon''(\omega) = \omega\tau\left(\frac{\varepsilon_s - \varepsilon_\infty}{1+\omega^2\tau^2}\right) \tag{20}$$

where ε_s is the static (DC) value of the permittivity and ε_∞ is the optical or very-high-frequency value of the permittivity. Pure free water at room temperature (at 25°C) has a relaxation time τ = 8.27 ps (Kaatze, 1989), which corresponds to a relaxation frequency of approximately 19 GHz. Therefore, free water losses will only start to have a significant effect with high-frequency surveys (i.e., above 500 MHz; Cassidy, 2009).

There are a number of mixing models that provide the dielectric permittivity of soil. One of the most popular models is an empirical model called Topp's equation (Topp et al., 1980), which describes the relationship between relative permittivity ε_r and volumetric water content θ_v of soil:

$$\varepsilon_r = 3.03 + 9.3\theta_v + 146\theta_v^2 - 76.6\theta_v^3 \tag{21}$$

$$\theta_v = -5.3\times10^{-2} + 2.92\times10^{-2}\varepsilon_r - 5.5\times10^{-4}\varepsilon_r^2 + 4.3\times10^{-6}\varepsilon_r^3 \tag{22}$$

The model is often considered inappropriate for clays and organic-rich soils, but it agrees reasonably well for sandy/loamy soils over a wide range of water contents (5-50%) in the GPR frequency range (10 MHz-1 GHz). The model does not account for the imaginary component of permittivity.

The complex refractive index model (CRIM) is valid for a wide variety of soils. The model uses knowledge of the permittivities of a material and their fractional volume percentages, and it can be used on both the real and imaginary components of the complex permittivity. The three-phase soil can be modelled with the complex effective permittivity of water ε_w, gas (air) ε_g and matrix ε_m as (Shen et al., 1985)

$$\varepsilon^e = \left\{\left(\phi S_w\sqrt{\varepsilon_w}\right) + \left[(1-\phi)\sqrt{\varepsilon_m}\right] + \left[\phi(1-S_w)\sqrt{\varepsilon_g}\right]\right\}^2 \tag{23}$$

where ϕ is the porosity and $S_w = \theta_v/\phi$ is the water saturation (e.g., the percentage of pore space filled with fluid). Fig. 7 shows the comparison of modelled dielectric permittivity using Topp's equation and CRIM for a sandy soil.

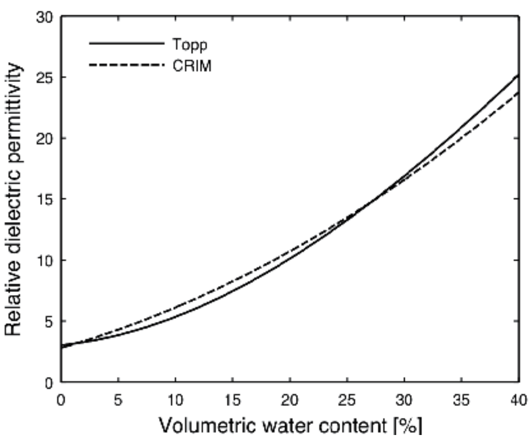


Fig. 7. The modelled dielectric permittivity using Topp's equation (solid line) and CRIM (dashed line) for sandy soil. The porosity and permittivity of the soil matrix are assumed to be ϕ = 40% and ε_m = 4.5, respectively.

2.4.2 Electric conductivity

Electric conductivity describes the ability of a material to pass free electric charges under the influence of an applied field. The primary effect of conductivity on electromagnetic waves is energy loss, which is expressed as the real part of the conductivity. The imaginary part contributes to energy storage and the effect is usually much less than that of energy loss. In highly conductive materials, the electromagnetic energy is lost as heat and thus the electromagnetic waves cannot propagate as deeply. Therefore, GPR is ineffective in materials such as those under saline conditions or with high clay contents (Cassidy, 2009).

Three mechanisms of conduction determine the bulk electric conductivity. The first is electron conduction caused by the free electrons in the crystal lattice of minerals, which can often be negligible. The second is electrolytic conductivity caused by the aqueous liquid containing dissolved ions in pore spaces. The third type of conductivity is surface conductivity associated with the excess charge in the electrical double layer at the solid/fluid interface, which is typically high for clay minerals and organic soil matter. This concentration of charge provides an alternate current path and can greatly enhance the electrical conductivity of a material (Knight & Endres, 2005). The bulk conductivity of sediments and soils can be modelled as (Knödel et al., 2007)

$$\sigma = \frac{\phi^m}{a}\sigma_w S_w{}^n + \sigma_q \tag{24}$$

with knowledge of the conductivity of the pore fluid σ_w, effective porosity ϕ and water saturation S_w, and where n, m and a are model parameters, i.e., a saturation exponent (often $n \sim 2$), a cementation exponent (m = 1.3-2.5 for most sedimentary rocks) and an empirical parameter (a = 0.5-1 depending on the type of sediment), respectively. The first term is according to Archie's law (Archie, 1942), which represents a contribution from electrolytic conductivity. The second term adds the contribution of the interface conductivity σ_q. At GPR frequencies, the conductivity is often approximated as real-valued static or DC conductivity (Cassidy, 2009).

2.4.3 Magnetic permeability

The magnetic property of soils is caused by the presence of ferrimagnetic minerals, mainly magnetite, titanomagnetite, and maghemite. These minerals either stem from the parent rocks or can be formed during soil genesis.

As discussed in previous sections, the magnetic properties theoretically influence the propagation of electromagnetic waves. However, in natural soils, the influence of the magnetic properties of the soil is fairly low in most cases. The magnetic permeability must be extremely high to influence the GPR signal. For example, Cassidy (2009) suggests that magnetic susceptibility $\kappa = (\mu/\mu_0) - 1$ must be greater than 30,000 x 10^{-5} SI to have an influence comparable to the dielectric permittivity. Soils exhibiting such high magnetic susceptibilities are extremely rare. Although tropical soils often display high susceptibilities, values in this range are exceptional (Preetz et al., 2008). Therefore, the magnetic permeability of most soils is usually assumed to be the same as that of free space, i.e., $\mu = \mu_0$ and $\mu_0 = 1$.

3. Soil moisture determination using GPR

There is a close relation between soil dielectric permittivity and its water content, as described in the previous section. GPR can be used to measure this proxy and the soil water content by implementing a variety of measurement and analysis techniques. They provide different sampling depths, and spatial and temporal resolutions and accuracies. Most of these techniques use a relation that links the permittivity of the soil to the propagation velocity of the electromagnetic waves (Eqs. 1 and 2). Other techniques determine the coefficient of reflection, which also depends on the dielectric permittivity of the materials (Eqs. 16 and 18).

	Transmission, traveltime	Reflection, traveltime (CO)	Reflection, traveltime (MO)	Diffraction, traveltime (CO)	Ground wave, traveltime	Reflection coefficient
Depth of investigation	Some 10 m	Metres	Metres	Metres	10 cm	A few cm
Accuracy	High	High	Low	Low	High	High
Spatial resolution	Medium - high	Medium	Low	Medium	High*	High*
Information on vertical moisture distribution	Yes	Yes	Yes	Yes	Limited	No
Cost (setup and data analysis)	High	Low	High	Medium	Low	Low
Requirements	Boreholes	Plane interfaces in the subsurface	Plane interfaces in the subsurface	Natural or artificial diffractors in the subsurface	Short vegetation, little surface roughness	Short vegetation, little surface roughness

Table 2. Summary of GPR methods used to measure water content and their qualitative rating (*: only in the lateral direction).

3.1 Transmission measurements

One straightforward way to deduce the electromagnetic wave velocity is to measure the time that a wave takes to travel along a known distance. For example, the travel path is known for borehole-to-borehole measurements (Fig. 6), assuming a homogeneous medium and a straight path. The mean wave velocity along the travel path can be easily calculated and the mean water content can be deduced. When using a tomographic layout with several interlacing travel paths (Fig. 6, right) and after inverting the data, we can obtain a high-resolution image of the soil water distribution between the boreholes. Tomographic borehole measurements have been successfully used to assess the water content distribution and, further, hydraulic properties (e.g., Tronicke et al., 2001; Binley et al., 2001). Tomographic measurements can also be applied from one borehole to the surface or if two or more sides of the study volume are accessible, e.g., by trenches (Schmalholz et al., 2004).

3.2 Reflection measurements with a known subsurface geometry

When using a common-offset (CO) configuration and if the depths of radar reflectors in the subsurface are known, the wave velocity can be determined using $v = 2d/t$, where d is the depth of the reflector and t is the two-way traveltime. In the case of a layered subsurface, every reflection can be analysed and the interval velocity within each layer can be calculated from the mean velocities with the Dix formula (Dix, 1955):

$$v_n = \left(\frac{\overline{v}_n^2 t_n - \overline{v}_{n-1}^2 t_{n-1}}{t_n - t_{n-1}} \right)^{1/2} \tag{25}$$

where v_n is the interval velocity of the nth layer, $\overline{v}_{n-1}$ and $\overline{v}_n$ are the stacking velocities from the datum to reflectors above and below the layer, and t_{n-1} and t_n are reflection arrival times.

The depth of reflectors can be obtained from boreholes or by digging a trench. Stoffregen et al. (2002) measured the water content of a lysimeter by analysing the traveltimes of the reflection at the bottom of the lysimeter. However in most cases, the depths of reflecting structures are not available, and the geometry of the subsurface and the electromagnetic characteristics have to be deduced from GPR measurements.

3.3 Multioffset measurements

If there is no knowledge about the geometry of the subsurface, further information is needed, which can be achieved by multioffset GPR measurements. Several acquisition layouts can be used to acquire multioffset data: common midpoint gather (CMP), wide angle reflection and refraction (WARR) gather (see Section 2.3.2), sequential constant offset measurements with different offsets or continuous multioffset measurements with multi channel GPR devices. After acquisition, all data can be converted to CMP sections by sorting the radar traces (e.g., Yilmaz, 2000; Greaves et al., 1996). With different antenna offsets, the waves take different propagation paths to and from a reflector in the subsurface (Fig. 5, right). A larger offset x results in a longer travel path and traveltime t:

$$t = \frac{2\sqrt{d^2 + (x/2)^2}}{v} \tag{26}$$

This equation describes a hyperbola, hence horizontal reflectors are mapped as reflection hyperbolas in a CMP radar section. Fig. 8 shows a CMP section from a sandy environment where the groundwater table is at 4.6 m depth. Several reflections at boundaries within the sand are visible. The first straight onset with a slope of $1/c_0$ is the airwave, a direct wave propagating through the air from the transmitter to the receiver. The second straight onset with a steeper slope of $1/v$ is the ground wave, followed by reflection hyperbolas from several reflectors in the subsurface. By fitting hyperbolas to some of the reflections, a depth-velocity model can be constructed that gives information on the water distribution. This model can also be used to transform the data from traveltimes to depth, analogous to seismic data processing (e.g., Yilmaz, 2000). When analysing multioffset data along a profile, a 2D velocity distribution of the subsurface and, thus, the water distribution can be deduced. This technique has been used successfully to map water content in the subsurface (e.g., Greaves et al., 1996; Bradford, 2008).

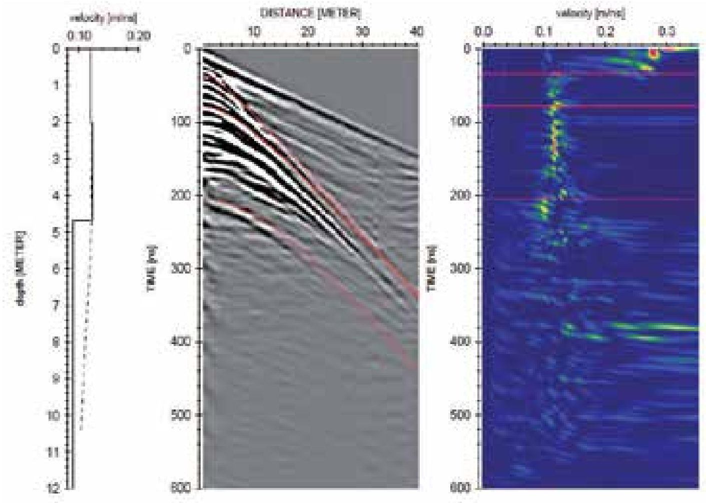


Fig. 8. Radar profile of the 80 MHz CMP measurement and fitted reflection hyperbolas (centre), semblance analysis (right) and velocity-depth model (left).

3.4 Diffraction measurements

Radar waves are diffracted by objects that are smaller than their wavelength, resulting in scattering in all directions. When performing a constant offset radar measurement, such objects cause a signal in the data before the antenna is directly above the object. When x is the lateral distance and d is the depth of the object relative to the antenna, the diffracted wave appears at

$$t = \frac{2\sqrt{d^2 + x^2}}{v_{soil}} \tag{27}$$

which describes a hyperbola. Objects causing such diffraction hyperbolas include stones, roots, pipes or wires if the antenna is moved perpendicular to their alignment. The mean wave velocity between the antenna and the object can be determined by fitting a synthetic hyperbola to the data and can be used to assess the mean water content above the object. This method has been used successfully to recover soil moisture distribution by analysing hyperbolas from natural objects or artificial objects that were placed in the subsurface (e.g., Igel et al., 2001; Schmalholz, 2007).

3.5 The ground wave

One of the most commonly used techniques for soil moisture mapping with GPR is analysing the ground wave velocity. For surface GPR measurements the ground wave is the only wave that travels through the ground with a propagation path that is known a priori, and the wave velocity can be calculated directly from the traveltime. Analysing the ground wave has proven to be a fast technique that can be used to map large areas and yield reasonable results in comparison to other methods, such as TDR or gravimetric soil moisture determination (Du, 1996; Grote et al., 2003; Huisman et al., 2001, 2003; Overmeeren et al., 1997).

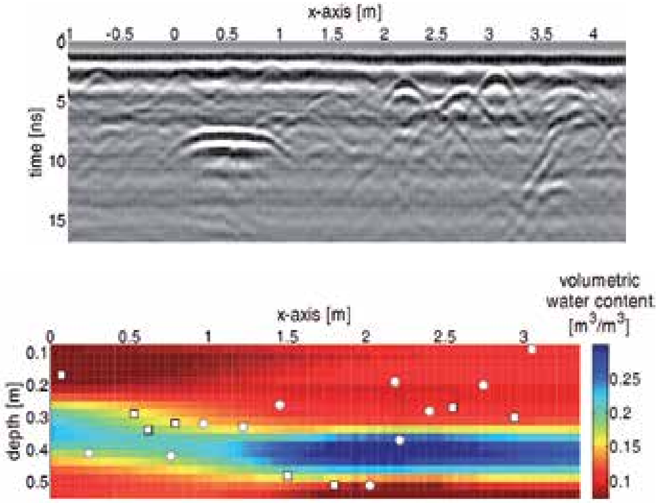


Fig. 9. Constant offset radar section (top) over an area with natural and artificial diffracting objects (metal bars, stones, roots) and the deduced water distribution based on the fit of diffraction hyperbolas (bottom). The circles and squares indicate the positions of objects that caused the diffractions used for the analysis (with permission from Schmalholz, 2007).

There are two principle modes by which a ground wave measurement can be carried out. The first is to perform a moveout (MO, WARR) or a CMP measurement (Overmeeren et al., 1997; Huisman et al., 2001). When plotting the traveltime versus the distance to the transmitter and receiver antennas, the airwave and the ground wave onsets form a straight line whose slope corresponds to the inverse of the wave velocity in air $1/c_0$ and soil $1/v_{soil}$, respectively (Fig. 10, left part, $x < x_{opt}$). The extension of the air and ground wave (dashed lines in Fig. 10) intersect at the origin. The second method is to carry out a constant offset (CO) measurement by measuring lateral changes in the velocity of the ground wave (Grote et al., 2003) (Fig. 10, right part, $x > x_{opt}$). In this mode, the water content distribution along a profile can be deduced rapidly. A combination of both methods was proposed by Du (1996) and is the most appropriate method to date.

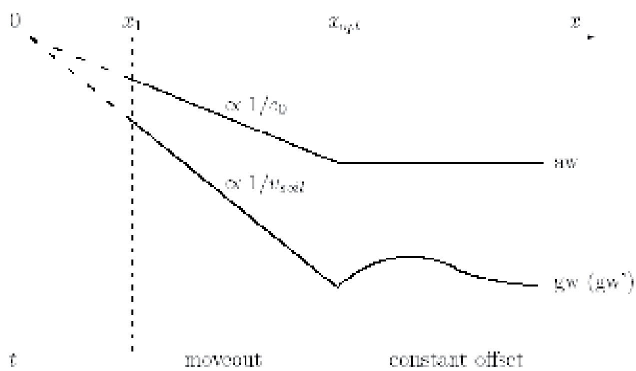


Fig. 10. Schematic traveltime diagram of a ground wave measurement consisting of moveout measurements from x_1 to x_{opt}, followed by a constant offset measurement for $x > x_{opt}$ (aw: air wave, gw: ground wave).

The ground wave technique is suited to map the water content of the topsoil over wide areas and to deduce its lateral distribution. The exact depth of investigation of the ground wave is still an object of research and is a function of antenna frequency, antenna separation and soil permittivity (e.g., Du, 1996; Galagedara et al., 2005). Fig. 11 shows an example of the result of the technique applied to a location with sandy soil that had been used as grassland. The area from x = 9 to 11 m was irrigated and shows higher water contents. TDR measurements were carried out every 20 cm along the same profile and show similar results.

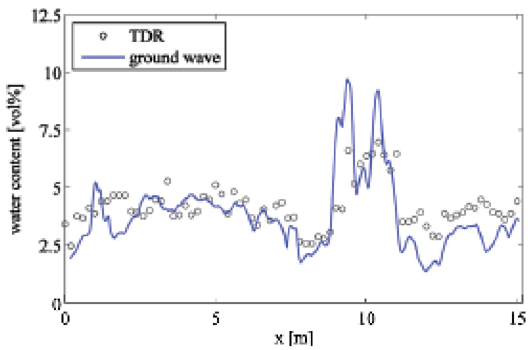


Fig. 11. Water contents obtained from ground wave field measurement of a sandy soil and results of TDR measurements. The area from 9 to 11 m has been irrigated and shows higher water contents.

3.6 Reflection coefficient at the soil surface

The reflection coefficient R of an incident wave normal to an interface is described in Eq. 18. Regarding the interface air-soil with ε_{air} = 1, we can deduce the coefficient of reflection R and, thus, the permittivity and the water content of the upper centimetres of the soil:

$$\varepsilon_{soil} = \left(\frac{1-R}{1+R} \right)^2 \tag{28}$$

This principle is also used to determine soil moisture in active remote sensing techniques over large areas (e.g., Ulaby et al., 1986). Fig. 12 shows a layout with an air-launched horn antenna mounted on a sledge so that it can be moved along profiles with a fixed distance from the soil. An example of this technique is demonstrated in Section 4.1.

3.7 Further techniques

In addition to these commonly used techniques, there are a variety of other techniques that can be used to deduce soil-water content by means of GPR. For example, Bradford (2007) analysed the frequency dependence of wave attenuation in the high-frequency range to assess water content and porosity from GPR measurements. Igel et al. (2001) and Müller et al. (2003) used guided waves that travel along a metallic rod that is lowered into a borehole. Van der Kruk (2010) analysed the dispersion of waves that propagate in a layered soil under certain conditions and Minet et al. (2011) used a full-waveform inversion of off-ground horn antenna data to map the moisture distribution of a horizontally layered soil.

Fig. 12. Experimental setup to determine the coefficient of reflection. A 1-GHz horn antenna is mounted on a sledge 0.5 m above the ground.

4. Application examples of GPR

In this section, two examples of GPR measurements and analyses applied for monitoring irrigation and subsequent events are given. Both examples demonstrate the ability of GPR to measure and monitor changes in the soil water content. The first example analyses reflections at the soil surface (see Section 3.6) and the second is transmission measurements between boreholes (see Section 3.1).

4.1 Monitoring of soil water content variation by GPR during infiltration

GPR measurements were carried out after irrigation to see its capability in monitoring the changes in soil dielectric properties and their spatial variation. This work demonstrates that the obtained GPR data can be used to describe the soil water distribution.

4.1.1 Experimental setup

An irrigation experiment was carried out on an outdoor test site in Hannover, Germany. The texture of the soil at the site is medium sand and the soil has a high humus content of 6.3%. The total pore volume (i.e., the maximum water capacity shortly after heavy rainfall or irrigation) of the soil is estimated to be 55 vol%. The field capacity (i.e., the maximum water content that can be stored against gravity) is approximately 21 vol%, which corresponds to a relative dielectric permittivity of 10.7 according to Topp's equation (Topp et al., 1980). The ground surface was relatively flat.

A one-square-metre area was irrigated at a rate of approximately 12 litres per minute for approximately one hour, i.e., 720 litres of water in total. An excess of water was applied to ensure that the pore system was filled to its maximum water capacity. The relative permittivity of the soil before and immediately after the irrigation was 4 and 20.8, which corresponds to a water content of 5.5 vol% and 35.5 vol%, respectively. Because the test was carried out during the summer and there had been no rainfall for more than a half month prior to the test, the soil was assumed to be in its driest natural condition prior to the irrigation.

A frequency-domain radar system was employed and operated at a frequency range of 0.5-4.0 GHz. Antennas with a constant separation of 6 cm were fixed at a height of 5 cm above the ground surface and scanned in 1D every two minutes on an approximately 1-m-long profile with the help of a scanner. Additionally, the relative permittivity was monitored at one location off the GPR scanning line by TDR every half minute. The TDR probes are 10 cm long and were stuck vertically in the topsoil. The configuration of the measurements is illustrated in Fig. 13. The data collection was continued after the irrigation was stopped. The relative permittivity measured by TDR and soil water content at the end of the irrigation were 14 and 26 vol%, respectively (see Fig. 16).

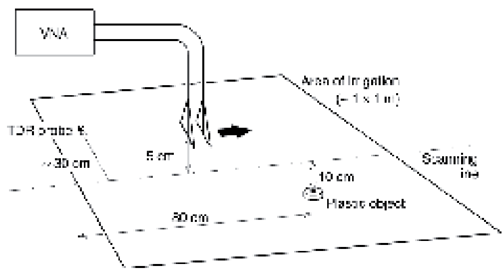


Fig. 13. Schematic illustration of the experimental setup.

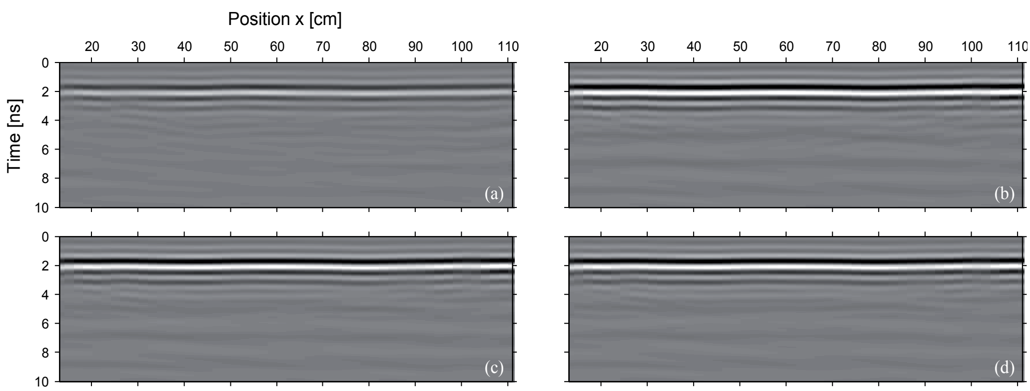


Fig. 14. Radar profiles acquired (a) before irrigation, (b) when irrigation was stopped, (c) one hour after irrigation stopped, and (d) two hours after irrigation stopped.

4.1.2 Data analysis and estimation of soil conditions

Some of the radar profiles obtained in the experiment are shown in Fig. 14. These profiles are plotted with the same colour scale. The reflections from the ground surface at 2 ns are weaker before irrigation (Fig. 14a) than after (Fig. 14b-d). This is because the reflection coefficient of the ground surface was increased by irrigation and the surface reflection became stronger. Thus, by analysing the surface reflection, it is possible to retrieve the soil water content at the soil surface as described in Section 3.5.

Fig. 15 shows waveforms acquired at the same location but at different times. The surface reflections appear at around 2 ns, but the peak amplitudes E^r are different. The amplitude of the reflection is expressed with a reflection coefficient R, following Eq. 14. The reflection coefficient of an obliquely incident electromagnetic wave with an electric field parallel to the interface is given by

$$R = \frac{Z_2 \cos\theta_1 - Z_1 \cos\theta_2}{Z_2 \cos\theta_1 + Z_1 \cos\theta_2} \tag{29}$$

where θ_1 and θ_2 are the angles of the incident and transmitted waves, respectively. The incident angle is determined by the measurement geometry. Z_1 and Z_2 are the intrinsic impedances of the first medium (air) and second medium (soil), respectively. The intrinsic impedance of air and incident angle are known, and the reflection amplitude was measured. Therefore, the intrinsic impedance of soil Z_2, the dielectric permittivity and the water content can be calculated from the above relationships. The only unknown is the strength of the incident wave E^i, which is often measured with a metal plate with R = 1 as calibration (Serbin & Or, 2003; Igel, 2007). In this experiment, the incident wave strength was obtained using a puddle on the ground caused by the excess water supply during the irrigation. Assuming the permittivity of the water is 81, the incident wave strength can also be obtained with the above equations. If there are changes in the surface topography, the amplitude of the incident wave changes at different locations because of the antenna radiation pattern, i.e., changes in spreading loss. However, the ground surface in this experiment was almost flat, as can be seen from the traveltimes of the reflected wave in Fig. 14, which are almost constant along the profile, so the effects of topography were neglected.

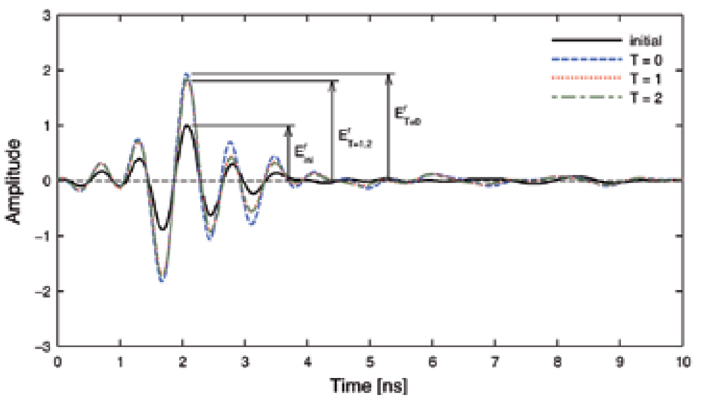


Fig. 15. Waveforms sampled before irrigation (in the dry condition, labelled "initial"), when irrigation was stopped (T = 0), and one and two hours after irrigation was stopped.

The estimated dielectric permittivity from GPR data at three positions along the profile are shown in Fig. 16 as a function of time after irrigation in comparison to the TDR measurements. The corresponding volumetric water content is also provided on the right axis using Topp's equation (Topp et al., 1980). Before irrigation, the permittivity values estimated from GPR measurements and measured by TDR are similar, but the estimated ones are slightly lower. This is because the TDR measures permittivity averaged over the measurement volume, which is about 10 cm deep, while the estimate using GPR is for a shallower region, perhaps a centimetre deep. In its dry condition, the ground surface may be drier than deeper regions, and the method could retrieve this difference. Furthermore, a lower bulk density in a shallower region leads to a lower bulk permittivity. At the time that irrigation was stopped, the water content measured by TDR was about 35 vol%, while the water content estimated by GPR was higher than 50 vol%. This indicates that within very shallow soil, most of the pore space was filled with water. After the irrigation was stopped, the measured water content slowly decreased exponentially to about 25 vol%, which is consistent with our estimate of the field capacity. The estimated water content also decreased with time, but the decrease was much more rapid than for the water content measured with TDR. This is also caused by the different sampling depths of the two methods: the shallower layer mapped by GPR loses water faster than the deeper soil horizons measured with TDR.

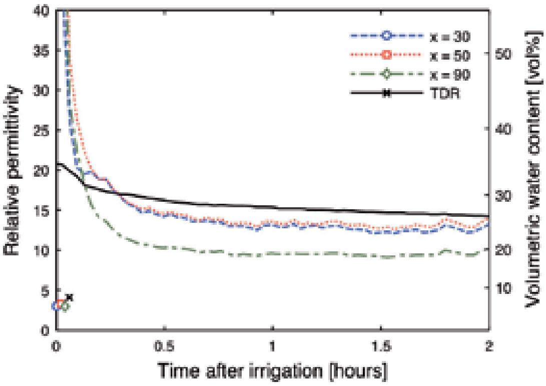


Fig. 16. The dielectric permittivity of the uppermost 10 cm of the soil measured by TDR (solid line) and permittivity of the ground surface estimated from GPR data, plotted as a function of time after the irrigation was stopped. Plots at the zero-time axis indicate permittivity before irrigation, i.e., the dry condition. The right axis gives the corresponding volumetric water content using Topp's equation (Eq. 22, Topp et al., 1980).

The dielectric permittivity of the ground surface can also be estimated depending on the position along the profile. The left side of Fig. 17 shows the spatial variation in permittivity and water content at different times as a function of the position. The water content, as well as its spatial variation, were not high in the dry condition, but both were increased by irrigation. The spatial distributions before and after irrigation are similar but not exactly the same. As shown in Fig. 16, most of the decrease in water content in the shallow region occurred within the first 30 minutes, and the calculated spatial water distribution at one and two hours after irrigation ceased are almost the same.

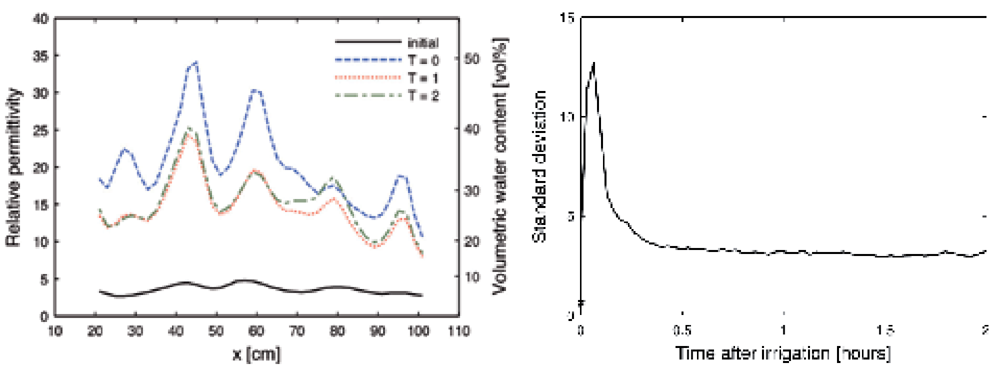


Fig. 17. Left: the spatial variation in dielectric permittivity of the ground surface estimated from GPR data. Right: the standard deviation of the estimated relative permittivity in space. The cross at time zero indicates the value before irrigation.

By further analysing the spatial variation of dielectric permittivity and water content, the soil water distribution can be understood. The right side of Fig. 17 shows the standard deviation of permittivity plotted as a function of time. The variation was very small for the dry condition. By adding water, the variation increased and continued to increase for about 10 minutes after irrigation was stopped. It then decreased and became stable but was still higher than for the dry condition. The result can be interpreted as water that had infiltrated and percolated into the ground during and shortly after irrigation, but the percolation velocity varies spatially on a small scale, depending on differences in bulk density, texture, humus content and related pore volume, i.e., water was drained faster in areas with higher proportions of transmission pores. The variation in percolation velocity caused a variation in water content and an increase in the standard deviation of permittivity for a short period of time after irrigation was stopped. Areas with a smaller pore volume may have stored more water than their field capacity for a short time, but the excess water subsequently percolated out. This behaviour led to a decrease in variation in permittivity. After some time, all sections stored as much water as the field capacity and the variation became stable, but remained higher than at the dry condition.

4.2 Infiltration monitoring by borehole GPR

An artificial groundwater recharge test was carried out in Nagaoka City, Japan (Kuroda et al., 2009). Time-lapse cross-hole measurements were performed at the same time to monitor the infiltration process in the vadose zone.

4.2.1 Field experiment

The borehole GPR measurement carried out during the infiltration experiment is schematically illustrated in Fig. 18. The top 2 m of soil consisted of loam, and the subsoil was sand and gravel. The groundwater table was located approximately 10 m below the ground surface. During the experiment, water was injected from a 2 x 2 m tank with its base set at a depth of 2.3 m. The total volume of water injected into the soil was 2 m^3, requiring approximately 40 minutes for all water to flow from the tank. Two boreholes were located on both sides of the tank with a separation of 3.58 m. Using these boreholes, GPR data were acquired in a ZOP configuration. In this mode, both the transmitter and receiver antennas were lowered to a common depth. Data were collected every 0.1 m at depths of 2.3-5.0 m. This required about 2 minutes to cover the whole depth range. A total of 25 profiles were obtained during the experiment, which lasted 322 minutes.

4.2.2 Estimation of percolation velocity

Three radar profiles acquired from this experiment are shown in Fig. 19. The first arrival times range from 36-38 ns in the initial, unsaturated state (Fig. 19a), and 42-44 ns in the final state (Fig. 19c), which is considered to be fully saturated. In the intermediate state of 51-53 minutes after infiltration, the first arrival times are almost identical to the initial state at depths below 4 m (Fig. 19b). Shallower than 4 m depth, the first arrival times are delayed: the shallower the depth, the greater the traveltime. This delay is caused by increased wetting in the vadose zone (transition zone).

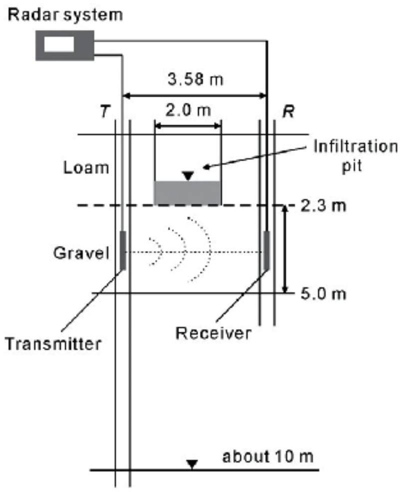


Fig. 18. Schematic sketch of the artificial ground water recharge test in the vadose zone.

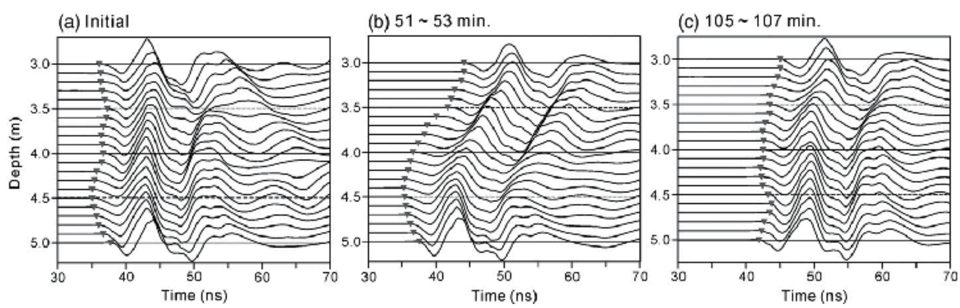


Fig. 19. Radar profiles observed during the infiltration test: (a) before infiltration, (b) 52 min after infiltration, and (c) 106 min after infiltration. Triangles show the picked first arrival times.

The infiltration process may not be 1D because the vadose zone is heterogeneous. Since the standard ZOP method relies on determining the velocity of an electromagnetic wave that follows a straight path from the transmitter to the receiver, the infiltration process is assumed to be 1D. Fig. 20 shows vertical profiles of the first arrival times. In these profiles, the volumetric water content at a specific depth is estimated based on the following procedure. By assuming a straight raypath, a first arrival time is used to calculate the velocity v using $v = d/t$, where d is the offset distance between the transmitter and the receiver, and t is the traveltime. By assuming that frequency-dependent dielectric loss is small (Davis and Annan, 1989), the apparent dielectric constant ε is obtained using Eq. 2. Finally, the volumetric water content θ can be estimated by substituting ε into the empirical Topp's equation (Eq. 22, Topp et al., 1980).

The spatial and temporal variations of volumetric water content are derived using all first arrival times collected during the infiltration experiment (Fig. 21). This illustration clearly shows the movement of the wetting front in the test zone during the infiltration process. The water content varies sharply from the unsaturated state (lower left side) to the saturated state (upper right side). The zone exhibiting significant changes can be interpreted as a transition zone. The average downward velocity of percolating water in the test zone is estimated to be about 2.7 m/h and is the boundary between the unsaturated and transition zones (Fig. 21).

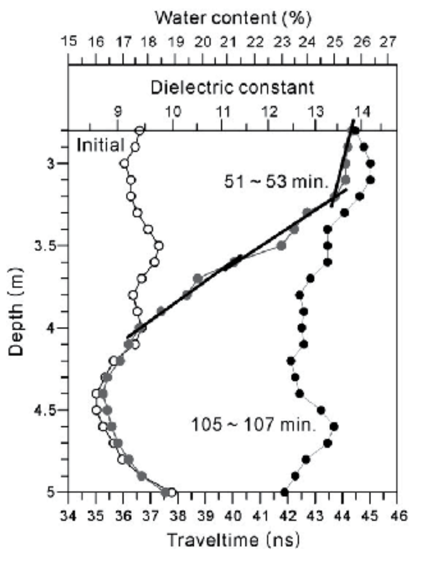


Fig. 20. First arrival times picked from the time-lapse ZOP radar profiles at three different conditions of the infiltration experiment. EM-wave velocities estimated using first arrival times are transformed into apparent dielectric constants and further converted into volumetric water contents.

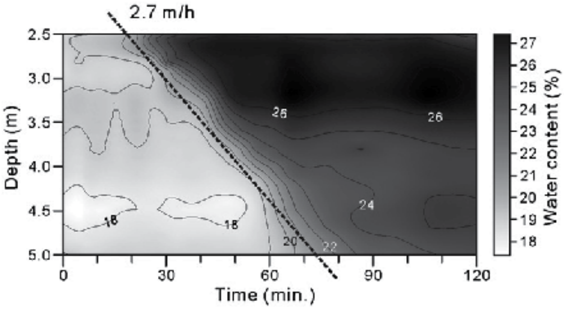


Fig. 21. A map showing the spatiotemporal variations in volumetric water content in the test zone during the infiltration process. The infiltrated water penetrated vertically with a velocity of about 2.7 m/h.

5. Conclusion

In this chapter, the basics of GPR and the principles for measuring soil water content are discussed. Two examples are given where GPR was used to monitor the temporal changes in soil water content following irrigation. The first example describes analysis of the reflection amplitude of electromagnetic waves, which depends on the dielectric permittivity and the water content of soil. This technique is very fast and can be used to obtain results with a very high spatial and temporal resolution. The second example utilised the fact that the velocity of the electromagnetic waves is determined by the dielectric permittivity and the water content of soil. Although this method requires boreholes to carry out a transillumination measurement, it can capture vertical changes in soil water content. These examples clearly demonstrated the capability of GPR to measure water-related soil properties. Compared to other methods for the measurement of soil water content, GPR can measure a larger area easily and quickly with a high spatial and temporal resolution. As shown in Section 3, there are a variety of techniques to measure or estimate the soil water content. Most of them are completely non-invasive, which is a very important feature for monitoring soil water content at the same location. One can chose the most suitable method according to the possible measurement setup and the desired type of result. Therefore, GPR has a great potential for use in investigations of irrigation and soil science.

6. List of symbols

c	Velocity of light in free space	m/s
d	Depth	m
f	Frequency	Hz
k	Wavenumber	1/m
t	Time	s
$\tan\delta$	Loss tangent	
v	Propagation velocity of electromagnetic waves	m/s
E	Electric field strength of an electromagnetic wave	V/m
E_0	Original electric field strength of an electromagnetic field	V/m
E^i	Incident electric field strength	V/m
E^r	Reflected electric field strength	V/m
E^t	Transmitted electric field strength	V/m
R	Reflection coefficient	
S_w	Water saturation	
T	Transmission coefficient	
Z	Intrinsic impedance	Ω
α	Attenuation constant	Np/m
α'	Attenuation constant	dB/m
β	Phase constant	1/m
δ	Skin depth	m
ε	Absolute dielectric permittivity	F/m
ε'	Real part of dielectric permittivity	F/m
ε''	Imaginary part of dielectric permittivity	F/m
ε_0	Absolute dielectric permittivity of free space	F/m
ε^e	Complex effective permittivity	F/m
ε_r	Relative dielectric permittivity	
ε_s	Low frequency static permittivity	F/m
ε_∞	High frequency permittivity	F/m
ϕ	Porosity	
λ	Wavelength	m

μ	Absolute magnetic permeability	H/m
μ_0	Absolute magnetic permeability of free space	H/m
μ_r	Relative magnetic permittivity	
θ_v	Volumetric water content	
σ	Electric conductivity	S/m
σ'	Real part of electric conductivity	S/m
σ''	Imaginary part of electric permittivity	S/m
σ_q	Interface conductivity	S/m
τ	Relaxation time	s
ω	Angular frequency	rad/s

7. References

Annan, A.P. (2005). Ground penetrating radar in near-surface geophysics, In: Near-Surface Geophysics, Investigations in Geophysics, No. 13, Society of Exploration Geophysics, Butler, D.K., pp.357-438, ISBN 1-56080-130-1, Tulsa, OK

Annan, A.P. (2009). Electromagnetic principles of ground penetrating radar, In: Ground Penetrating Radar: Theory and Applications, Jol, H.M., pp. 3-40, Elsevier, ISBN 978-0-444-53348-7, Amsterdam, The Netherlands

Archie, G.E. (1942). The electrical resistivity log as an aid in determining some reservoir characteristics. Petroleum Transactions of AIME, Vol. 146, pp. 54-62

Binley, A., Winship, P., Middleton, R., Pokar, M. & West, J. (2001). High-resolution characterization of vadose zone dynamics using cross-borehole radar. Water Resources Research, Vol. 37, pp. 2639-2652

Bradford, J.H. (2007). Frequency-dependent attenuation analysis of ground-penetrating radar data. Geophysics, Vol. 72, pp. J7-J16

Bradford, J.H. (2008). Measuring water content heterogeneity using multifold GPR with reflection tomography. Vadose Zone Journal, Vol. 7, pp. 184-193

Cassidy, N.J. (2009). Electrical and magnetic properties of rocks, soils, and fluids, In: Ground Penetrating Radar: Theory and Applications, Jol, H.M., pp. 41-72, Elsevier, ISBN 978-0-444-53348-7, Amsterdam, The Netherlands

Daniels, D.J. (Ed.). (2004). Ground Penetrating Radar (2nd Edition), IEE, ISBN 0-86341-360-9, London

Davis, J.L. & Annan, A.P. (1989). Ground-penetrating radar for high resolution mapping of soil and rock stratigraphy. Geophysical Prospecting, Vol. 37, pp. 531-551

Dix, C.H. (1955). Seismic velocities from surface measurements. Geophysics, Vol. 20, pp. 68-86

Du, S. (1996). Determination of Water Content in the Subsurface with the Ground Wave of Ground Penetrating Radar. Dissertation, Ludwig-Maximilians-Universität, München, Germany

Galagedara, L.W., Redman, J.D., Parkin, G.W., Annan, A.P. & Endres, A.L. (2005). Numerical modeling of GPR to determine the direct ground wave sampling depth. Vadose Zone Journal, Vol. 4, pp. 1096-1106

Greaves, R.J., Lesmes, D.P., Lee, J.M. & Toksoz, M.N. (1996). Velocity variations and water content estimated from multi-offset ground penetrating radar, Geophysics, Vol. 61, pp. 683-695

Grote, K., Hubbard, S. & Rubin, Y. (2003). Field-scale estimation of volumetric water content using ground-penetrating radar ground wave techniques. Water Resources Research, Vol. 39, pp. 1321-1333

Huisman, J.A., Sperl, C., Bouten, W. & Verstaten, J.M. (2001). Soil water content measurements at different scales: accuracy of time domain reflectometry and ground-penetrating radar. Journal of Hydrology, Vol. 245, pp. 48-58

Huisman, J.A., Hubbard, S.S., Redman, J.D. & Annan, A.P. (2003). Measuring soil water content with ground penetrating radar: a review. Vadose Zone Journal, Vol. 2, pp. 476-491

Igel, J., Schmalholz, J., Anschütz, H.R., Wilhelm, H., Breh, W., Hötzl, H. & Hübner C. (2001). Methods for determining soil moisture with the ground penetrating radar (GPR). Proceedings of the Fourth International Conference on Electromagnetic Wave Interaction with Water and Moist Substances, Weimar, Germany.

Igel, J. (2007). On the Small-Scale Variability of Electrical Soil Properties and Its Influence on Geophysical Measurements. PhD Thesis, Johann Wolfgang Goethe-Universität, Frankfurt am Main, Germany

Kaatze, U. (1989). Complex permittivity of water as a function of frequency and temperature. Journal of Chemical and Engineering Data, Vol. 34, pp. 371-374

Knight, R.J. & Endres, A.L. (2005). An introduction to rock physics principles for near-surface geophysics, In: Near-Surface Geophysics, Investigations in Geophysics, No. 13, Society of Exploration Geophysics, Butler, D.K., pp.357-438, ISBN 1-56080-130-1, Tulsa, OK

Knödel, K., Lange, G., & Voigt, H.-J. (Eds.). (2007). Environmental Geology, Handbook of Field Methods and Case Studies, Springer, ISBN 978-3-540-74669-0, Berlin

Kuroda, S., Jang, H. & Kim, H.J. (2009). Time-lapse borehole radar monitoring of an infiltration experiment in the vadose zone. Journal of Applied Geophysics, Vol. 67, pp. 361-366

Lampe, B. & Holliger, K. (2003). Effects of fractal fluctuations in topographic relief, permittivity and conductivity on ground-penetrating radar antenna radiation. Geophysics, Vol. 68, pp. 1934-1944

Minet, J., Wahyudi, A., Bogaert, P., Vanclooster, M., & Lambot, S. (2011). Mapping shallow soil moisture profiles at the field scale using full-waveform. Geoderma, Vol. 161, pp. 225-237

Müller, M., Mohnke, O., Schmalholz, J. & Yaramanci, U. (2003). Moisture assessment with small-scale geophysics - the Interurban project. Near Surface Geophysics, Vol. 1, pp. 173-181

Noborio, K. (2001). Measurement of soil water content and electrical conductivity by time domainreflectometry: a review. Computers and electronics in agriculture, Vol. 31, 213-237

Overmeeren, R.A., Sariowan, S.V. & Gehrels, J.C. (1997). Ground penetrating radar for determining volumetric soil water content; results of comparative measurements at two test sites. Journal of Hydrology, Vol. 197, pp. 316-338

Preetz, H., Altfelder, S. & Igel, J. (2008). Tropical soils and landmine detection – an approach for a classification system. Soil Science Society of America Journal, Vol. 72, pp. 151-159

Robinson, D.A., Jones, S.B., Wraith, J.M., Or, D. & Friedmann, S.P. (2003). A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. Vadose Zone Journal, Vol. 2, pp. 444-475

Schmalholz, J., Stoffregen, H., Kemna, A. & Yaramanci, U. (2004). Imaging of Water Content Distributions inside a Lysimeter using GPR Tomography. Vadose Zone Journal, Vol. 3, pp. 1106-1115

Schmalholz, J. (2007). Georadar for small-scale high-resolution dielectric property and water content determination of soils. Dissertation, Technical University of Berlin, Germany

Serbin, G. & Or, D. (2003). Near-surface soil water content measurements using horn antenna radar: methodology and overview. Vadose Zone Journal, Vol. 2, pp. 500-510

Shen, L.C., Savre, W.C., Price, J.M. & Athavale, K. (1985). Dielectric properties of reservoir rocks at ultra-high frequencies, Geophysics, Vol. 50, pp. 692-704

Stoffregen, H., Zenker, T., Wessolek, G. (2002). Accuracy of soil water content measurements using ground penetrating radar: Comparison of ground penetrating radar and lysimeter data. Journal of Hydrology, Vol. 267, pp. 201-206

Takahashi, K., Preetz, H. & Igel, J. (2011). Soil properties and performance of landmine detection by metal detector and ground-penetrating radar – Soil characterisation and its verification by a field test. Journal of Applied Geophysics, Vol. 73, pp. 368-377

Topp, G.C., Davis, J.L. & Annan, A.P. (1980). Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resource Research, Vol. 16, pp.574-582

Tronicke, J., Tweeton, D.R., Dietrich, P. & Appel, E. (2001). Improved crosshole radar tomography by using direct and reflected arrival times. Journal of Applied Geophysics, Vol. 47, pp. 97-105

Ulaby, F.T., Moore, R.K. & Adrian, K.F. (1986). Microwave Remote Sensing: Active and Passive, volume 3: From Theory to Applications. Artech House, ISBN 0-89006-192-0, Norwood, MA

van der Kruk, J., Jacob, R.W. & Vereecken, H. (2010). Properties of precipitation-induced multilayer surface waveguides derived from inversion of dispersive TE and TM GPR data. Geophysics, Vol. 75, pp. WA263-WA273

Yilmaz, O. (2000). Seismic data analysis - processing, inversion, and interpretation of seismic data (2nd edition). Society of Exploration Geophysicists, ISBN 978-0931830464, Tulsa, OK

9

A Low Cost Remote Monitoring Method for Determining Farmer Irrigation Practices and Water Use

Kristoph-Dietrich Kinzli
Florida Gulf Coast University
USA

1. Introduction

Irrigated agriculture has traditionally been the backbone of the rural economy and provides nearly 70% of the worlds food supply using only 30% of planted agricultural land. Irrigated agriculture in general is a large water user that consumes roughly 80% of freshwater supplies worldwide and in the Western United States (Oad et al. 2009; Oad and Kullman, 2006). Since irrigated agriculture uses a large and visible portion of surface water in the world and the Western United States, it is often targeted for increased efficiency to free water for other uses. Due to fish and wildlife concerns, and demands from a growing urban population, the pressure to reduce consumption by irrigated agriculture increases every year. As the world population continues to grow, irrigated agriculture will also need to meet the additional food production required. The current belief is that irrigated agriculture will need to maximize the crop per drop to meet the demand in the future. The problem lies in the fact that available water supplies are currently developed and new untapped sources are limited. In order to increase production with the current amount of available water and deal with external pressure for reduced water usage, irrigated agriculture has to become more efficient in its on-farm water application and its deliveries on a whole system scale. Decision Support Systems and modernization of infrastructure can be used on a large system scale to increase the efficiency of water deliveries and have been utilized successfully in New Mexico, China, Spain and Argentina (Oad et al. 2009; Gensler et al. 2009; FAO, 2006; Gao, 1999; FAO, 1994). The problem with large infrastructure improvement projects and large scale implementation of decision support systems is that significant capital is required in addition to organizational structures that allow for such massive undertakings.

One sector where irrigated agriculture can significantly reduce water usage and stretch every drop is in on-farm water delivery. Achieving high water use efficiencies on farm requires detailed knowledge about soil moisture and water application rates to optimally manage irrigation. The problem with achieving improved efficiency is that high efficiency is generally coupled with high cost on-farm monitoring systems. Such high cost monitoring set ups are generally prohibitive to small farmers in the United States and in irrigated areas throughout the world. Additionally, the traditional methods of measuring water application require a constant presence on farm and do not allow for remote monitoring.

This chapter will focus on a low cost methodology utilized to remotely instrument eight farm fields in the Middle Rio Grande Valley. The chapter will describe in detail the instrumentation of the farm fields including soil moisture sensors and low cost flow measuring devices. The chapter will also present results regarding water usage and farmer irrigation practices that were obtained from the low cost instrumentation method. It is the hope of the author that this type of low cost monitoring network finds acceptance and contributes to improvements in water use efficiency throughout the American West and beyond, allowing irrigated agriculture to meet growing demand in the future with limited water supplies.

2. Background

The Middle Rio Grande Conservancy District (MRGCD) may be one of the oldest operating irrigation systems in North America (Gensler et al. 2009). Prior to Spanish settlement in the 1600s the area was being flood irrigated by the native Pueblo Indians. At the time of Albuquerque's founding in 1706 the ditches, that now constitute the MRGCD, were already in existence and were operating as independent acequia (tertiary canal) associations (Gensler et al. 2009). In 2010 the MRGCD operated and maintained nearly 1,500 miles of canals and drains throughout the valley in addition to nearly 200 miles of levees for flood protection. The MRGCD services irrigators from Cochiti Reservoir to the Bosque del Apache National Wildlife Refuge. An overview map of the MRGCD is displayed in Figure 1. Irrigation structures managed by the MRGCD divert water from the Rio Grande to service agricultural lands, that include both small urban landscapes and large scale production of alfalfa, corn, vegetable crops such as chili and grass pasture. The majority of the planted acreage, approximately 85%, consists of alfalfa, grass hay, and corn which can be characterized as low value crops. In the period from 1991 to 1998, USBR crop production and water utilization data indicate that the average irrigated acreage in the MRGCD, excluding pueblo lands, was 53,400 acres (21,600 ha) (Kinzli 2010). Analysis from 2003 through 2009 indicates that roughly 50,000 acres (20,200 ha) are irrigated as non-pueblo or privately owned lands and 10,000 acres (4,000 ha) are irrigated within the six Indian Pueblos (Cochiti, San Felipe, Santo Domingo, Santa Ana, Sandia, and Isleta). Agriculture in the MRGCD is a $142 million a year industry (MRGCD, 2007). Water users in the MRGCD include large farmers, community ditch associations, six Native American pueblos, independent acequia communities and urban landscape irrigators. The MRGCD supplies water to its four divisions -- Cochiti, Albuquerque, Belen and Socorro -- through Cochiti Dam and Angostura, Isleta and San Acacia diversion weirs, respectively (Oad et al. 2009; Oad et al. 2006; Oad and Kinzli, 2006). In addition to diversions, all divisions except Cochiti receive return flow from upstream divisions.

Return flows are conveyed through interior and riverside drains. From the drains, excess water is diverted into main canals in the downstream divisions for reuse or eventual return to the Rio Grande. Drains were originally designed to collect excess irrigation water and drain agricultural lands, but are currently used as interceptors of return flow and as water conveyance canals that allow for interdivisional supply.

Water in the MRGCD is delivered in hierarchical fashion; first, it is diverted from the river into a main canal, then to a secondary canal or lateral, and eventually to an acequia or small ditch. Figure 2 displays the organization of water delivery in the MRGCD. Conveyance canals in the MRGCD are primarily earthen canals but concrete lined canals exist in areas where bank stability and seepage are of special concern. After water is conveyed through laterals it is delivered to the farm turnouts with the aid of check structures in the lateral canals. Once water passes the farm turnout it is the responsibility of individual farmers to apply water and it is applied to fields using basin or furrow irrigation techniques. The overall average yearly water diversion by the MRGCD is approximately 350,000 Acre-feet (Kinzli 2010).

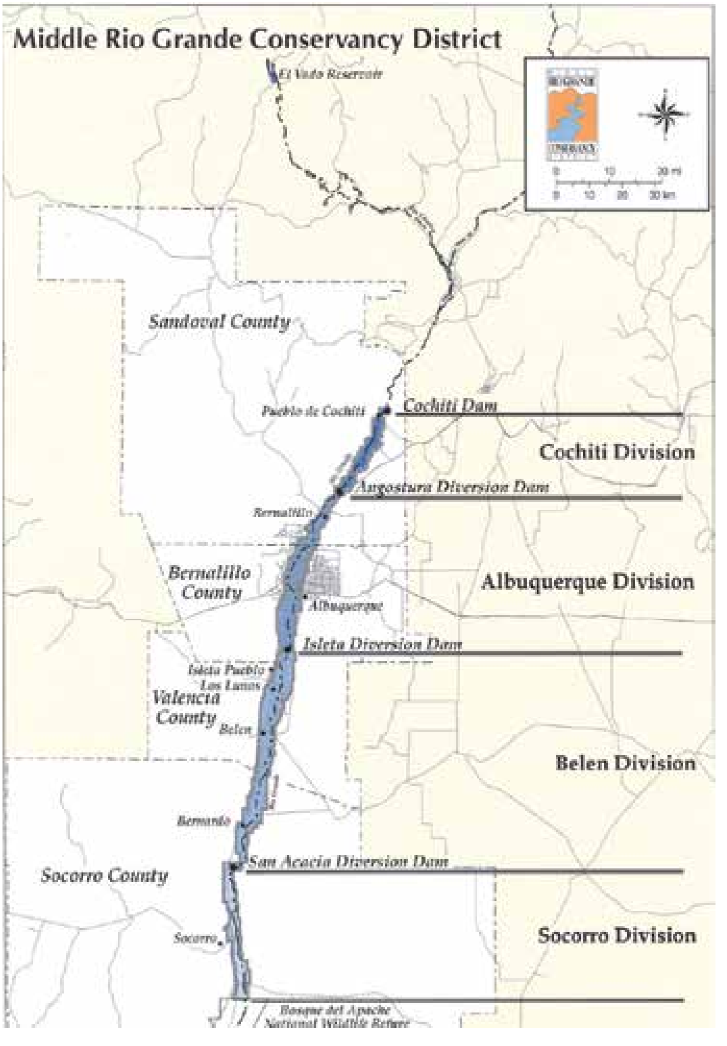


Fig. 1. Overview Map of MRGCD (MRGCD, 2007)

The MRGCD like many other conservancy districts has come under pressure to become a more efficient water user. In order to do so large scale infrastructure modernization projects have been undertaken (Gensler et al. 2009) and a decision support system has been developed and implemented (Kinzli, 2010). The one sector remaining where water saving can be realized is at the farm level by improving farmer irrigation application efficiency.

Measurements of on-farm application efficiency in the MRGCD were limited and therefore in the summer of 2008 eight fields in the MRGCD were instrumented to measure total water application and application efficiency. Figure 3 displays a map of the eight instrumented fields.

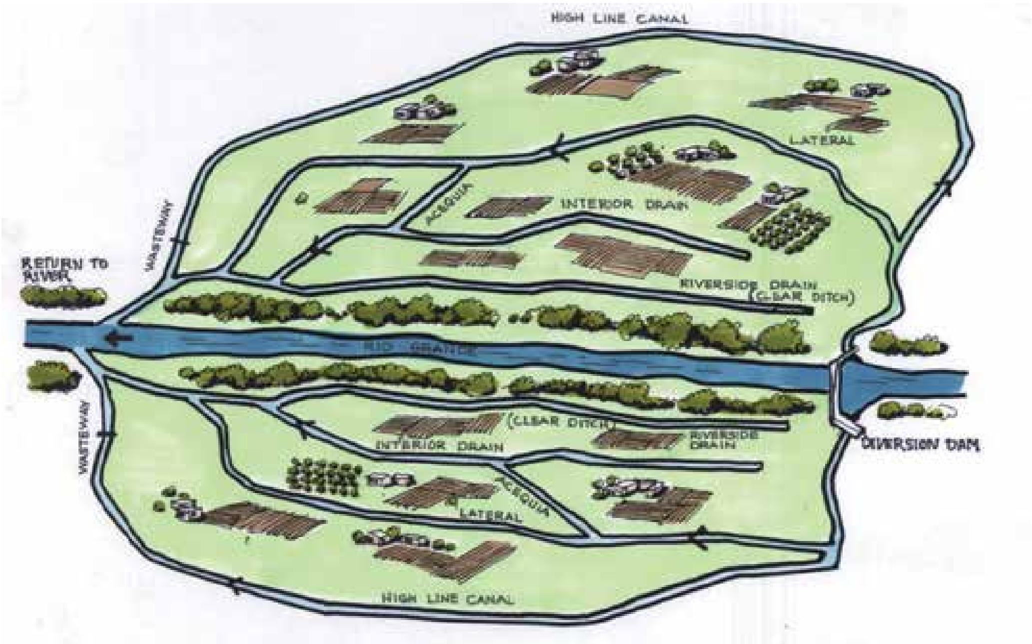


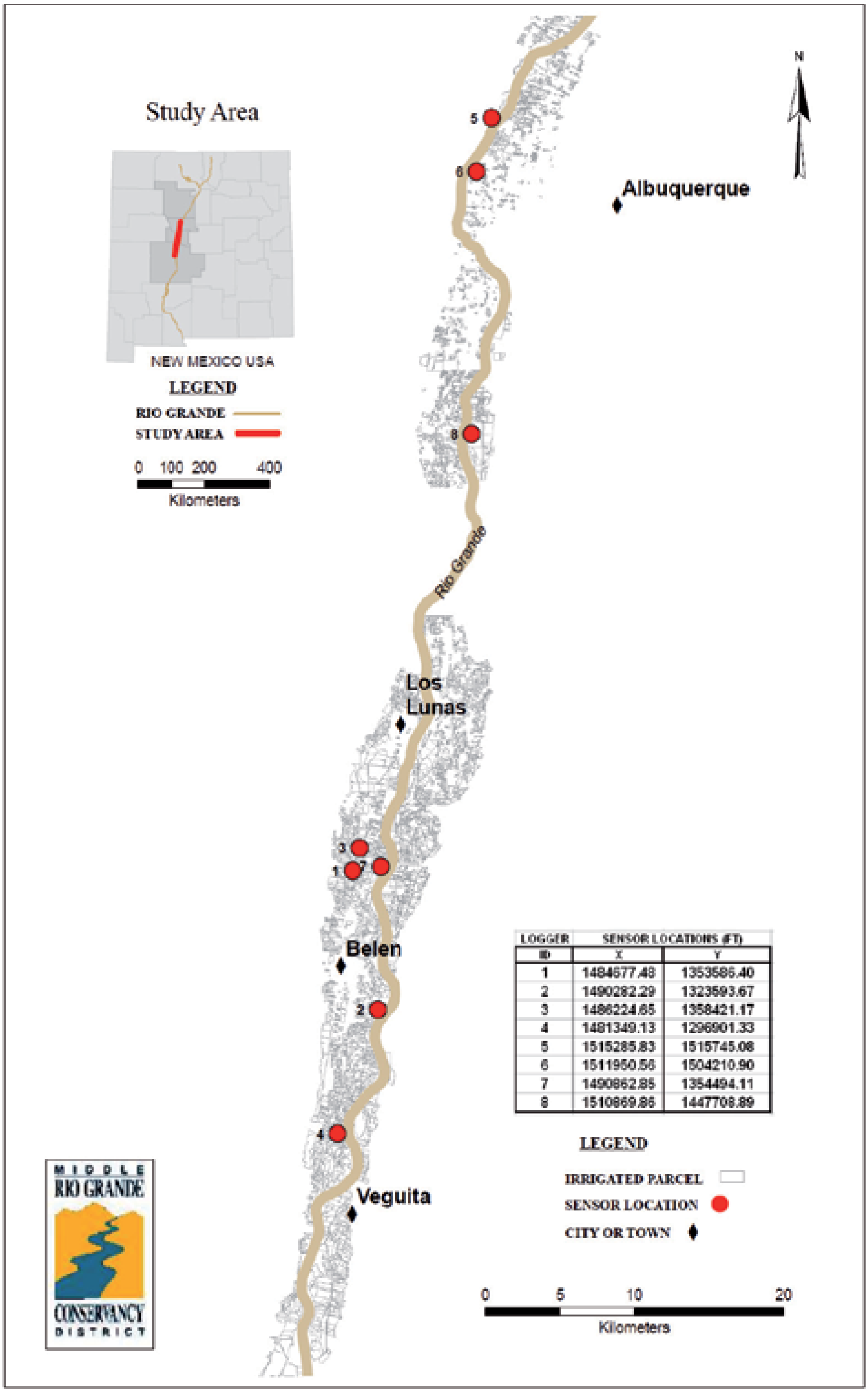
Fig. 2. Representation of MRGCD Irrigation System (Courtesy of David Gensler and MRGCD)

3. Methodology

In order to measure total water application and application efficiency it was necessary to instrument the eight fields with both a flow measurement device and instruments to measure soil moisture. Since the main crops in the MRGCD are alfalfa and grass hay 4 fields of each were chosen for monitoring. Due to the financial constraint of limited funding it was necessary to utilize a low cost setup with the total cost for each field remaining under $1200. This financial constraint would be a realistic consideration for farmers in the MRGCD as well since they produce low value crops such as alfalfa and grass hay. The use of a low cost monitoring network would also allow for application worldwide, specifically in developing countries.

3.1 Flow measurement

The first step in the field instrumentation was to perform a survey to determine the slope of the irrigation head-ditch, which was conducted using a laser level. The irrigation head ditches in the MRGCD are trapezoidal and have a 1 foot bottom width and a 1:1 H:V side slope. In addition to the survey, the dimensions of each head ditch were also determined. During the first irrigation event, the flow rate used for irrigation was measured using a Price



LOGGER	SENSOR LOCATIONS (FT)	
ID	X	Y
1	1484677.48	1353586.40
2	1490282.29	1323593.67
3	1486224.65	1358421.17
4	1481349.13	1296901.33
5	1515285.83	1515745.08
6	1511950.56	1504210.90
7	1490862.85	1354494.11
8	1510869.86	1447708.89

Fig. 3. Map of the Instrumented Farm Fields

Pygmy or Marsh McBirney flow meter and standard USGS measuring techniques. From the collected flow measurement and ditch data, it was possible to design a broad crested weir for flow measurement using the Unites States Bureau of Reclamation software Winflume and the Manning's flow rate equation. The software allows the user to design the appropriate flume and develops a stage-discharge equation based on the head over the crest of the weir. Figure 4 displays the flume designed for Field 3.

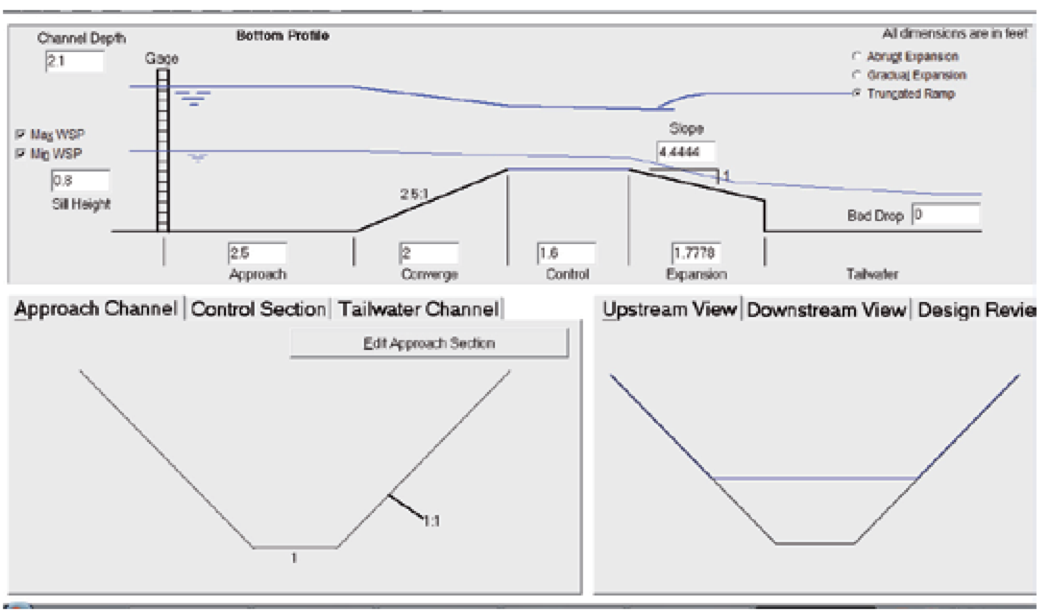


Fig. 4. Flume Designed for Measuring Field 3 (WSP = Water Surface Profile)

The broad crested weirs for each field were constructed out of concrete using cutout particle board templates as forms and cost approximately $100 each. Broad crested weirs were constructed for each of the eight fields but were utilized on seven fields. One farmer complained that the weir diminished his available flow rate, and therefore a rating curve was developed for his canal section instead of the weir. Figure 5 displays the finished broad crested weir for Field 3.

Hobo pressure transducers and data loggers ($400), manufactured by Onset Incorporated, were installed to measure the depth of water over the crest of the weir. These pressure transducers have an accuracy of 0.01 ft. Figure 6 displays a HOBO pressure transducer.

The Hobo dataloggers were installed on the side of each irrigation ditch roughly two canal widths upstream of the weir crest (Winflume design standard) using a small length of PVC pipe, clips, and concrete anchors. The section of PVC pipe was perforated multiple times with a ¼ inch drill bit to insure that water would seep into the section of PVC and allow for pressure measurement. Once the Hobo data loggers were installed in the PVC pipe a laser level was used to determine the offset between the bottom of the pressure transducer and the top of the weir crest. Figure 7 displays an installed Hobo pressure transducer.

Fig. 5. Completed Broad Crested Weir for Field 3

Fig. 6. Hobo Pressure Transducer

Fig. 7. Installed Hobo Pressure Transducer

The Hobo data loggers were set to log the absolute pressure every ten minutes. During an irrigation event, the pressure read by the Hobo included atmospheric pressure, so the atmospheric pressure from a Hobo exposed to only the atmosphere was subtracted from the reading. This resulted in a pressure reading that represented the total depth of water in the irrigation ditch. The pressure reading was converted using the conversion factor that 1 psi is the equivalent of 27.68 inches of water. Once the total depth of water in the irrigation ditch was calculated, the previously mentioned laser leveled offset of the weir crest was subtracted from the total water depth to get the depth of water over the weir crest. This value was plugged into the weir flow rate equation developed in Winflume to determine the flow passing the weir every ten minutes. Once the first irrigation event had occurred for each broad crested weir, the flow measurements calculated using the equation were compared to the initial measurement using flow meters in order to insure that the weirs were functioning properly. For each constructed weir the flow rate given by the Winflume equation was reasonable and corresponded to the measurements obtained using flow meters. The nature of this setup allowed for remote monitoring in that no on-farm presence was required during any irrigation event during the irrigation season. The Hobo pressure transducer has the capability to store an entire years worth of irrigation data and therefore data was only collected infrequently. When data was collected the Hobo optical USB cable was utilized to connect the pressure transducer to a laptop.

The total water volume in cubic feet applied during each irrigation event was obtained incrementally for every ten minute period during the irrigation event. The total volume in cubic feet was calculated by taking the flow rate in cubic feet per second every ten minutes and multiplying this value by 600 seconds. This was done for every ten minute interval during the duration of the irrigation event to obtain the total cubic feet of water applied during the event. This assumption to use a ten minute interval was validated by the fact that the water level did not fluctuate significantly during most irrigation events.

3.2 Soil moisture measurement

To improve irrigation efficiency the amount of moisture that is stored in the soil for beneficial plant use during the irrigation event and the subsequent depletion of the moisture is required. To measure the soil moisture, soil moisture probes were installed in each of the eight fields. During early 2008 before the irrigation season, soil moisture probes were installed in the eight representative fields instrumented with broad crested weirs. Electrical conductivity sensors were used instead of time domain reflectrometry (TDR) sensors due to budget constraints. TDR sensors can cost over $2000 a piece greatly, exceeding the budget available for each field. The electrical conductivity sensors used were the EC-20 ECHO probe from Decagon ($100 each). Figure 8 displays the EC-20 soil moisture probe.

Fig. 8. EC-20 ECHO Probe from Decagon Devices

Recent improvements to the ECH20 soil moisture sensor allowed for detailed measurement of soil water content (Sakaki et al. 2008). The ECH2O EC-20, which offers a low cost alternative to other capacitance type meters, (Kizito et al. 2008; Saito et al. 2008; Sakaki et al. 2008; Bandaranayake et al. 2007; Nemali et al. 2007; Plauborg et al. 2005) has been used to improve irrigation management for citrus plantations (Borhan et al. 2004). The precision of the ECH20 EC-20 is such that it can be used for greenhouse operations and to schedule field irrigation (Nemali et al. 2007). The main benefit of the ECH2O sensor is that it is one of the most inexpensive probes available and therefore can be widely used and implemented (Christensen, 2005; Luedeling et al. 2005; Riley et al. 2006). The ECH2O sensor is designed to be buried in the soil for extended periods of time and connected to a data logger such as the Em5b (Decagon Devices, Pullman WA). EC-20 sensors allow for the determination of saturation, field capacity, and wilting point, along with the redistribution pattern of soil water, and possible drainage below the root zone. This information can be used to decide the time and amount of irrigation (Bandaranayake et al. 2007).

The EC-20 probe has a flat design for single insertion and allows for continued monitoring at a user defined interval. The overall length of the sensor is 8 inches with a width of 1.2 inches and blade thickness of 0.04 inches, with a 2.4 inch sensor head length. The total sampling volume of the probe is between 7.8 and 15.6 in^3, depending on soil water content (Bandaranayake et al. 2007). The ECH2O EC-20 soil probe measures the dielectric permittivity or capacitance of the surrounding soil medium, and the final output from the sensor is either in a millivolt or raw count value that can be converted to a volumetric water content using calibration equations (Kelleners et al. 2005). The raw count is an electrical output specific to which datalogger the sensor is used with. Raw counts can easily be converted if an output in millivolts is desired. Details on the EC-20 sensor measurement principle and function are reported by the manufacturer (Decagon Devices, 2006a). Studies have shown that temperature affects on the ECH2O probes are minimal (Kizito et al. 2008; Norikane et al. 2005; Campbell, 2002) with changes of 0.0022 ft^3/ft^3 water content per degree C (Nemali et al. 2007). Problems due to soil variation and air gaps can be avoided by using the factory installation tool and developing calibration equations relevant to each soil type. Drawbacks of this sensor include water leakage into the sensor circuit in isolated cases, and damage from animals such as gophers and squirrels (Bandaranayake et al. 2007). Using the manufacturer provided equation, typical accuracy in medium textured soil is expected to be ±0.04 ft^3/ft^3 (3% average error) with soil specific equations producing results with an accuracy of ±0.02 ft^3/ft^3 (1% average error) (Decagon Devices, 2006b).

Through previous research it has been found that dielectric sensors often require site specific calibration either through field methods or laboratory analyses. Inoue et al (2008) and Topp et al (2000) found that it was necessary to perform site specific calibrations for capacitance sensors to account for salinity concerns, and Nemali et al (2007) found that it was necessary to calibrate the ECH2O sensors because output was significantly affected by the electrical conductivity of the soil. Other studies have found that site specific corrections are required for mineral, organic, and volcanic soils (Paige and Keefer, 2008; Bartoli et al. 2007; Regelado et al. 2007; Malicki et al. 1996).

Kizito et al. (2008) suggested that soil specific calibrations are important when large networks of ECH2O soil moisture sensors are deployed. Several researchers have found that soil specific calibrations are necessary for ECH20 probes across varying soil types (Sakaki et al. 2008; Mitsuishi and Mizoguchi, 2007; Fares and Polyakov, 2006; Bosch, 2004) and Saito et al (2008) found that calibration is a requirement for accurate determination of volumetric water content using the ECH2O. Based on the recommendations of these previous studies, soil specific calibrations were performed for each sensor installation using a technique described in (Kinzli, 2010). The use of EC20 ECHO sensors allowed for development of a low cost monitoring network capable of being used to schedule irrigation and therefore offer the possibility of improving water use efficiency.

The EC-20 ECHO probes installed in the eight fields were linked to Em5b data recorders ($400 each). The Em5b is a 5-channel, self-contained data recorder (Decagon, 2008). The Em5b is housed in a white UV-proof enclosure, which makes it suitable for general outdoor measurements. It uses 4 AAA-size alkaline batteries, that last 5-6 months, and has a Flash Data memory that allows for 145 days of data collection at 1 scan/hour (Decagon, 2008). All eight Em5b data loggers were set to record soil moisture every 60 minutes during the study. Figure 9 displays the Em5b data logger.

Fig. 9. Em5b-Datalogger from Decagon Devices

The EC-20 ECHO moisture probes were installed in the eight representative fields to obtain a value of soil moisture remaining before an irrigation event and to determine hourly soil moisture depletions. Each field was equipped with one sensor station, due to project budget constraints. Therefore each field represented a point measurement. This approach resulted in eight point measurements throughout the MRGCD. Lundahl (2006) showed that soil moisture measurements at one point in each field were sufficient to obtain soil moisture depletion and application efficiency in the MRGCD. The field layout used for each sensor station is displayed in Figure 10. The layout of the moisture probes was designed to eliminate data points in areas that display variable wetting front values due to distance and the points chosen provided average values for the field in question. Each sensor station consisted of two EC-20 ECHO probes (installed at 8 inches and 24 inches) so that a soil profile of up to 4 feet could be measured. Figure 11 displays the layout of a sensor station.

The Em5b data loggers were located outside of the field boundary to minimize interference with cultivation and prevent damage of the logger. A 50 ft extension cable was used to place the sensor stations out in the field to eliminate edge effects on crop ET. The 50 ft extension cable was placed in a hand dug trench out into the field at a depth of roughly 8 inches.

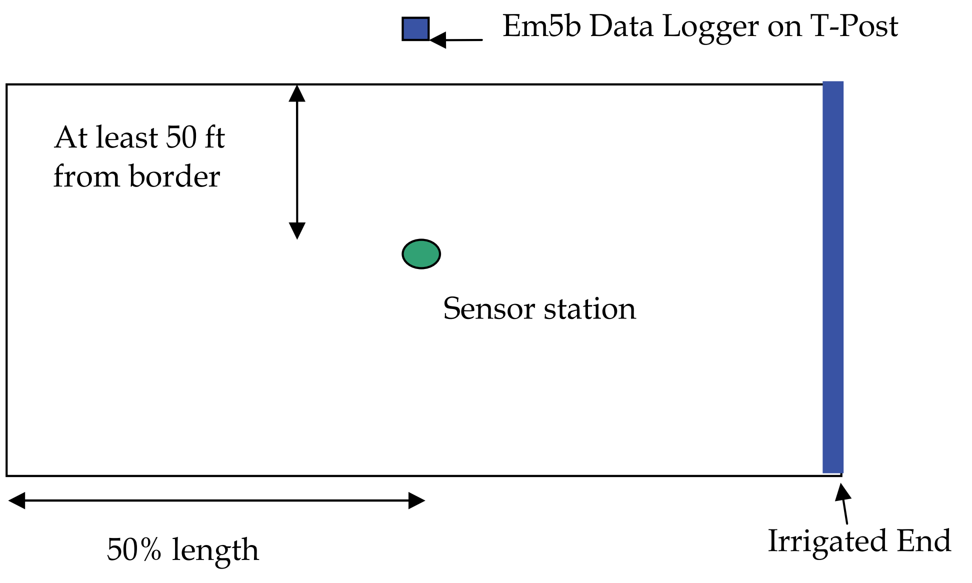


Fig. 10. Field Layout of Sensor Stations

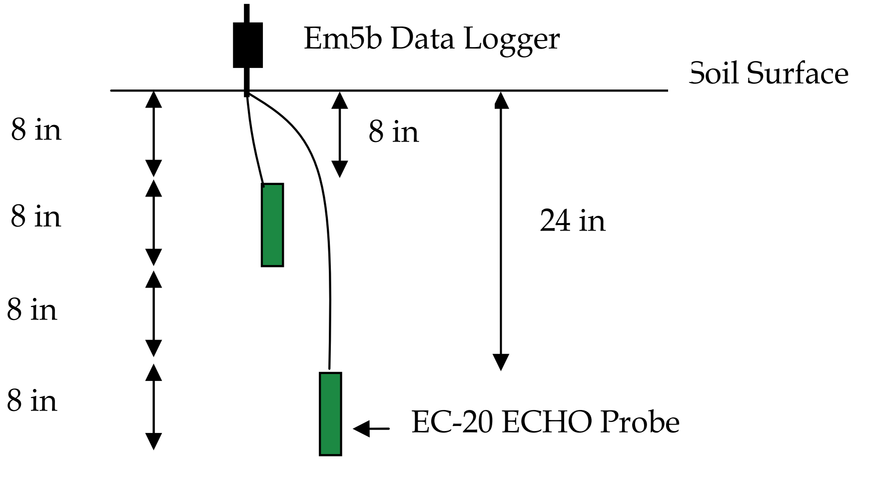


Fig. 11. Individual Layout of Sensor Stations

Once the soil moisture probes were installed, GPS points were taken at the location of the sensor station, datalogger, and the corner of the field to determine the exact irrigated acreage. From this collected data and the MRGCD aerial photography coverage, a detailed map of the flume, sensor, and datalogger location was created for each of the eight study fields. Figure 12 displays the map of Field 3.

Fig. 12. Map of Study Field 3

In order to validate that the probes were indeed functioning correctly and to develop calibration equations soil samples were taken in proximity to the installed sensor stations. A one gallon soil sample was taken for each installed sensor and analyzed at Colorado State University to determine soil type, field bulk density, pH, and electrical conductivity. Soil samples were also taken in order to determine field capacity, wilting point, and readily available moisture (RAM) for each soil type. These samples were also used to develop soil specific calibration equations for each sensor.

Using the instrumented fields it was possible to determine the on-farm application efficiency over a period of 2 years and 144 irrigation events for the eight instrumented fields. For the purpose of this analysis the on farm application efficiency was defined as the water replenished for crop use divided by the total water applied. This definition of application efficiency focuses only on water for crop growth and does not include any water used for leaching salts out of the root zone.

4. Results

In order to determine application efficiency the broad crested weirs and pressure transducers installed on the eight farm fields were used to determine the total water delivered for each irrigation event during the 2008 and 2009 irrigation seasons. Once the total water applied for an irrigation event was calculated, it was possible to calculate the depth of water applied per unit area by dividing the total volume applied by the acreage of the basin that was irrigated. This resulted in a depth of water in inches applied over the monitored field. Additionally, irrigation event number, the date, duration, and average flow rate for each irrigation event were recorded. Table 1 displays the logger ID, irrigation event, irrigation date, total water applied, and inches applied for ten irrigation events.

Logger ID	Irrigation Event	Date	Total Water Applied (ft^3)	Depth Applied (inches)
1	1	4/14/2008	157190	6.95
1	2	5/5/2008	266004	7.44
1	3	6/1/2008	325216	9.09
1	4	6/24/2008	149748	4.19
1	5	8/6/2008	150338	4.2
1	6	9/12/2008	125121	3.5
1	1	4/13/2009	112475	3.15
1	2	5/11/2009	148812	4.16
1	3	6/18/2009	173791	4.86
1	4	7/20/2009	113443	3.17

Table 1. Logger ID, Irrigation Event, Date, Total Water Applied and Depth Applied for 10 Irrigation Events

The next step in calculating the application efficiency was determining the water available for crop use that was replenished during each irrigation event. This was possible using the data collected from the installed EC-20 soil moisture sensors. The soil moisture sensor data, corrected using the developed laboratory calibration equations for each specific sensor installation, provided the volumetric soil moisture content before the irrigation event and after field capacity was reached. The difference between the volumetric water content before the irrigation event and field capacity represented the amount of water stored in the root zone for beneficial crop use. This data was recorded at both the 8 inch and 24 inch sensor location for each field for each irrigation event. To calculate the water stored in the soil for beneficial crop use in inches the 8 inch sensor was deemed to be representative of the first 16 inches of root depth for both the alfalfa and grass hay fields. The 24 inch sensor was chosen to represent the subsequent 20 inches of root depth for grass hay and the subsequent 32 inches for alfalfa. For grass hay and alfalfa this represented a 36 inch and 48 inch effective total root zone, respectively. These values were chosen based on 12 years of research conducted by Garcia et al. (2008) at the Natural Resource Conservation Service (NRCS), which was conducted in the Middle Rio Grande and Mesilla Valleys to determine the root depths that were effectively able to utilize and deplete soil moisture.

Once the effective root depth was determined, the root depth associated with each sensor and crop type was multiplied by the difference between the volumetric water content at field capacity and volumetric water content before the irrigation event took place for the 8 inch and 24 inch sensor. This yielded the water available for crop use in inches for the upper

16 inches and either lower 20 inches for grass hay or 32 inches for alfalfa. These two values were added together to give the total water in inches available for crop use applied during the irrigation event. The total water available for crop use was then divided by the total water applied to determine application efficiency. The application efficiency for all 144 irrigation events was calculated from the collected data. **Table 2** displays the results of the application efficiency analysis for 10 irrigation events.

Logger ID	Irrigation Event	Date	Depth Applied (inches)	Moisture Applied for Crop Use (inches)	Application Efficiency (%)
1	1	4/14/2008	6.95	4.64	67%
1	2	5/5/2008	7.44	1.92	26%
1	3	6/1/2008	9.09	3.36	37%
1	4	6/24/2008	4.19	2.24	53%
1	5	8/6/2008	4.2	1.76	42%
1	6	9/12/2008	3.5	2.4	69%
1	1	4/13/2009	3.15	2.56	81%
1	2	5/11/2009	4.16	2.56	62%
1	3	6/18/2009	4.86	2.56	53%
1	4	7/20/2009	3.17	1.12	35%

Table 2. Irrigation Event, Date, Depth Applied, Moisture Applied for Beneficial Crop Use and Application Efficiency for 10 Irrigation Events

The data displayed significant variability with a range in application efficiency from 8% to 100%. The mean value for all 144 irrigation events was found to be 44.4% with a standard deviation of 24.4%. The calculated mean value represent a lower application efficiency value than the 50% previously hypothesized by water managers.

To address the variability in the collected data a histogram of the collected data was created. Figure 13 displays the histogram of application efficiency.

The developed histogram displayed a nearly normal distribution about the mean value but was skewed slightly to the right due to 11 irrigation events with an application efficiency of 100%. From the developed histogram it became clear that the majority of irrigation events exhibited application efficiencies reflected by the calculated mean value.

Using the developed histogram it was also possible to calculate the probability that the application efficiency would fall within one standard deviation of the calculated mean. The probability that the application efficiency of an irrigation event would fall within one standard deviation was found to be 112 out of 144 irrigation events resulting in a probability value of 0.78. This indicates that 78% of the irrigation events were within one standard deviation of the calculated mean. Based on the analysis of the histogram and probability the revised value for application efficiency of 45% will be utilized by the MRGCD, which will allow for more precise representation of farmer practices. Several irrigation events exhibited an application efficiency of 100% and indicate possible under irrigation. Such results also point to possible measurement errors and residual moisture that is used by plants but not accounted for in calculations related to an irrigation event. One reason for possible errors could be due to the fact that only one sensor location was installed for each field due to budget constraints. Spatial variability in soil and topography that could not be measured due to a single sensor location could be the cause of uneven water distribution during the irrigation event. Differences in moisture uptake by plants due to spatial root variability could also be the cause this discrepancy.

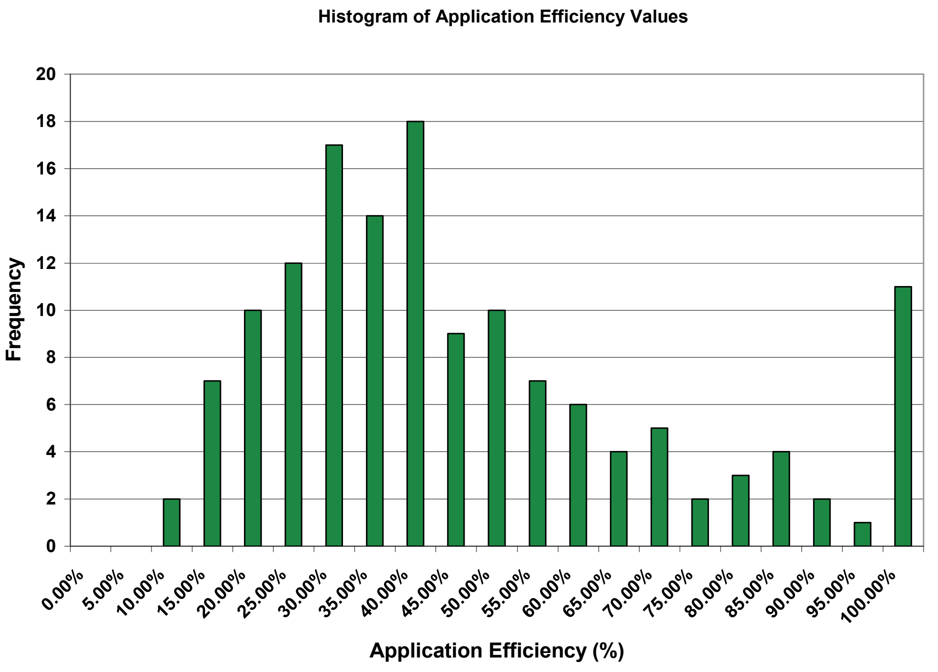


Fig. 13. Histogram of Application Efficiency

From the collected data it was also possible to refine the analysis of on farm application efficiency. First, the application efficiency was separated by crop type as analysis of the total water applied during an entire season suggested that fields with alfalfa hay would have higher application efficiency. The mean value of application efficiency for each grass field was calculated for the 2008 and 2009 irrigation seasons from all irrigation events. For 2008 the application efficiencies covered a range from 31% to 50%. For 2009 the application efficiency covered a range from 22% to 52%. The mean application efficiency of all 40 grass hay irrigation events was found to be 40.8% in 2008. The mean application efficiency of all 43 grass hay irrigation events was found to be 38.6% in 2009. Table 3 displays the average values found for each individual grass field.

The mean value of application efficiency for each alfalfa field was also calculated for the 2008 and 2009 irrigation seasons for all irrigation events. For 2008 the application efficiencies covered a range from 29% to 82%. For 2009 the application efficiency covered a range from 23% to 85%. The mean application efficiency of all 31 alfalfa hay irrigation events was found to be 50.2% in 2008. The mean application efficiency of all 30 alfalfa hay irrigation events was found to be 52.5% in 2009. Table 4 displays the average values found for each individual alfalfa field.

Logger ID	Crop Type	Application Efficiency 2008	Application Efficiency 2009
4	Grass Hay	50%	52%
5	Grass Hay	44%	41%
7	Grass Hay	33%	36%
8	Grass Hay	31%	22%

Table 3. Mean Application Efficiency for Grass Hay Fields in 2008 and 2009

Logger ID	Crop Type	Application Efficiency 2008	Application Efficiency 2009
1	Alfalfa Hay	49%	66%
2	Alfalfa Hay	29%	23%
3	Alfalfa Hay	82%	85%
6	Alfalfa Hay	45%	43%

Table 4. Mean Application Efficiency for Alfalfa Hay Fields in 2008 and 2009

The results show that the mean application efficiency for the alfalfa fields was 9.4% higher than the grass hay fields in 2008 and 13.9% higher in 2009. The temporal variation of the application efficiency numbers was also examined but no useful trends could be identified. Overall, the application efficiency numbers obtained during the study indicate that farmers in the MRGCD could improve their water management which would result in more water being available for other uses including increased production to meet the needs of our ever growing population.

5. Conclusions

As the world population continues to grow, irrigated agriculture will need to meet the additional food production required. The current belief is that irrigated agriculture will need to maximize the crop per drop to meet the demand in the future as current water supplies are already stretched thin. In order to increase production with the current amount of available water and deal with external pressure for reduced water usage, irrigated agriculture can become more efficient in its on-farm water application. Increasing on-farm application efficiency if often cost prohibitive, especially for low value crops. This chapter presented a low cost methodology utilized to remotely instrument eight farm fields in the Middle Rio Grande Valley for measurements of both applied irrigation water and soil moisture conditions. Through the instrumented fields it was possible to determine application efficiencies for 144 irrigation events over a period of 2 years. The total cost for each instrumented field was $1200 dollars and represents a cost level that most farmers in the Western United States could bear regardless of crop value.

The field instrumentation presented in this study was only used to monitor the eight fields and describe how farmers currently irrigate in the MRGCD. In order to achieve higher application efficiencies and obtain the most crop per drop the field instrumentation setup described in this chapter could be used to schedule irrigation events and precisely apply the appropriate amount of water. Knowledge of the soil moisture conditions prior to an irrigation event could be obtained from EC-20 sensor setups and an optimal application depth could be calculated. This application depth could then be precisely applied using the broad crested weirs placed in irrigation head ditches. It is the hope of the author that this type of low cost monitoring network finds acceptance and contributes to improvements in water use efficiency throughout the American West and beyond allowing irrigated agriculture to meet growing demand in the future with limited water supplies.

6. References

Bandaranayake, W.M., Borhan, M.S., and J.D. Holeton. 2007. Performance of a capacitance-type soil water probe in well-drained sandy soil. Soil Sci.Soc. Am. J. 71(3): 993 – 1002.

Bartoli, F., Regalado, C.M., Basile, A., Buurman, P. & Coppola, A. 2007. Physical properties in European volcanic soils: a synthesis and recent developments. In: Soils of volcanic regions in Europe, pp. 515–537. Springer-Verlag, Berlin.

Borhan, M.S., L.R. Parsons, and W. Bandaranayake. 2004. Evaluation of a low cost capacitance ECH2O soil moisture sensor for citrus in a sandy soil. p. 447–454. *In* Int. Irrig.

Bosch, D.D. 2004. Comparison of capacitance-based soil water probes in coastal plain soils. Vadose Zone Journal. 3: 1380-1389.

Campbell, C.S. 2002. Response of ECH2O Soil Moisture Sensor to Temperature Variation. Application Note. Decagon Devices, Pullman, WA.

Christensen, N.B., 2005. Irrigation management using soil moisture monitors. Western Nutrient Manage. Conf., 6: 46-53.

Decagon (2008). Environmental Research Instrumentation. ECH_2O Probe models EC-5, EC-10 and EC-20. http://www.decagon.com/echo/ec20.html

Decagon Devices, Inc., 2006a. ECH2O Dielectric Probes vs Time Domain Reflectometers (TDR). Decagon Devices Inc. Application Note. Decagon Devices, Inc., Pullman, Wash.

Decagon Devices, Inc., 2006b. ECH2O Soil Moisture Sensor Operator's Manual For Models EC-20, EC-10 and EC-5 Version 5. Decagon Devices, Inc., Pullman, WA. pp: 23.

Fares, A. and V. Polyakov, 2006. Advances in crop water management using capacitive water sensors. Adv. Agron. 90: 43-77.

Gao, Z. 1999. Decision making Support System for Irrigation Water management of Jingtai Chuan Pumping Irrigation Scheme at the Upper Reaches of Yellow River. Watsave Workshop Paper Presented at 51st IEC, Cape Town, South Africa

Garcia, R. 2008. New Mexico Integrated Water Management Handbook. United States Department of Agriculture, Natural Resources Conservation Service.

Gensler, D. Oad, R. and Kinzli, K-D. 2009. Irrigation System Modernization: A Case Study of the Middle Rio Grande Valley. ASCE Journal of Irrigation and Drainage. 135(2): 169-176.

Gensler, D. 2005. Interviews with David Gensler MRGCD Head Hydrologist, May-August

Inoue, M., Ould Ahmed, B.A., Saito, T., Irshad, M., and K.C. Uzoma. 2008. Comparison of three dielectric moisture sensors for measurement of water in saline sandy soils. Soil Use and Manag. 24: 156-162

Kelleners, T.J., D.A. Robins, P.J. Shouse, J.E. Ayars, and T.H. Skaggs. 2005.
Frequency dependence of the complex permittivity and its impact on
dielectric sensor calibration in soils. Soil Sci. Soc. Am. J. 69:67–76.

Kinzli, K-D. 2010. Improving Irrigation System Performance through Scheduled Water Delivery in the Middle Rio Grande Conservancy District. Dissertation. Colorado State University. May.

Kizito, F., Campbell, C.S., Campbell, G.S., Cobos, D.R., Teare, B.L., Carter, B., and J.W. Hopmans. 2008. Frequency, electrical conductivity and temperature analysis of a low-cost capacitance soil moisture sensor. J. of Hyd. 352 (3-4) 367-378.

Luedeling, E., M. Nagieb, F. Wichern, M. Brandt, M. Deurer and A. Buerkert, 2005. Drainage, salt leaching and physico-chemical properties of irrigated man-made terrace soils in a mountain oasis of northern Oman. Geoderma, 125: 273-285.

Lundahl, A. 2006. Quantifying, Monitoring, and Improving the Efficiency of Flood Irrigation in the Hydrosphere of Candelaria Farms Preserve, Albuquerque, New Mexico. Masters Thesis. Water Resources Program, University of New Mexico. Albuquerque, New Mexico.

Malicki, M.A., Plagge, R. & Roth, C.H. 1996. Improving the calibration
of dielectric TDR soil moisture determination taking into account the solid soil. European Journal of Soil Science, 47, 357–366.

Mitsuishi, S., and M. Mizoguchi. 2007. Effects of Dry Bulk Density and Soil Type on Soil Moisutre Measurements using ECH2O-TE Probe. ASA-CSSA-SSSA International Annual Meeting. Nov 4-8. New Orleans, LA.

MRGCD. 2007. Middle Rio Grande Conservancy District – Keeping the Valley Green. Flyer of the Middle Rio Grande Conservancy District. Middle Rio Grande Conservancy District. Albuquerque, New Mexico.

Nemali, K.S, Montesano, F., Dove, S.K. and M. W. van Iersel. 2007. Calibration and performance of moisture sensors in soilless substrates: ECH2O and Theta probes. Sci. Hort. 112(2): 227-234

Norikane, J.H., J.J. Prenger, D.T. Rouzan-Wheeldon, and H.G. Levine. 2005. A comparison of soil moisture sensors for space fl ight applications. Appl. Eng. Agric. 21:211–216.

Oad, R. Garcia, L. Kinzli, K-D, Patterson, D and N. Shafike. 2009. Decision Support Systems for Efficient Irrigation in the Middle Rio Grande Valley. ASCE Journal of Irrigation and Drainage. 135(2): 177-185.

Oad, Ramchand and K. Kinzli. 2006. SCADA Employed in Middle Rio Grande Valley to Help Deliver Water Efficiently. Colorado Water – Neswletter of the Water Center of Colorado State University. April 2006,

Oad, Ramchand and R. Kullman. 2006. Managing Irrigated Agriculture for Better River Ecosystems—A Case Study of the Middle Rio Grande. Journal of Irrigation and Drainage Engineering, Volume 132, No. 6: 579-586.

Plauborg, F. 1995. Evaporation from bare soil in a temperature humid climate. Measurement using micro-lysimeters and TDR. Agriculture and Forest Meteorology, 76, 1–17.

Paige, G.B., and T.O. Keefer. 2008. Comparison of field performance of multiple soil moisture sensors in a semi-arid rangeland. J. Am. Water Resources Association. 44(1): 121-135.

Regalado, C.M., Ritter, A. & Rodrı´guez, G..R.M. 2007. Performance of the commercial WET capacitance sensor as compared with time domain reflectometry in volcanic soils. Vadose Zone Journal, 6, 244–254.

Riley, T.C., T.A. Endreny and J.D. Halfman, 2006. Monitoring soil moisture and water table height with a low-cost data logger. Comput. Geosci., 32: 135-140.

Saito, T., Fujimaki, H., and Inoue, Mitsuhiro. 2008. Calibration and Simultaneous Monitoring of Soil Water Content and Salinity with Capacitance and Four-electrode Probes. American Journal of Environmental Sciences 4 (6), 690 - 699

Sakaki, T., Limsuwat, A., Smits, K.M., and T.H. Illangasekare. 2008. Empirical two-point α-mixing model for calibrating the ECH2O EC-5 soil moisture sensor in sands. Water Resources Research 44: 1-8.

Topp, G.C., Zegelin, S. & White, I. 2000. Impact of real and imaginary components of relatively permittivity on time domain reflectometry measurement in soils. Soil Sci. Soc. Am. J. 64, 1244–1252.

10

Critical Evaluation of Different Techniques for Determining Soil Water Content

Alejandro Zermeño-González[1], Juan Munguia-López[2], Martín Cadena-Zapata[1], Santos Gabriel Campos-Magaña[1], Luis Ibarra-Jiménez[2] and Raúl Rodríguez-García[1]
[1]Antonio Narro Autonomous Agrarian University
[2]Department of Agricultural Plastics
Research Center for Applied Chemistry, Saltillo, Coahuila
México

1. Introduction

To efficiently operate any type of irrigation system, it is necessary to know when to irrigate and the quantity of water to apply during irrigation. To achieve this, it is very important to know the previously available soil water content. A good on-farm irrigation water management requires a routine monitoring of soil water moisture. Soil water must be maintained between a lower and upper limit of availability for an optimum plant growth. Soil moisture is a very dynamic variable that depends on plants evapotranspiration, irrigation frequency, drainage and rainfall. Measuring soil water content for determining the water depth allows avoiding the economic losses due to the effect of underirrigation on crop yield and crop quality, and the environmentally costly effects of overirrigation on wasted water and energy, leaching of nutrients or agricultural chemicals into groundwater supplies.

This chapter describes the applications and limitations of different techniques for determining soil water moisture. A description of how to calculate the irrigation depth as a function of water soil holding capacity, soil depth and bulk density is also included. Six techniques for measurement of soil moisture are described: gravimetric sampling, neutron scattering, tensiometers, porous blocks, time domain reflectometry, impedance and capacitance methods.

2. State of water in the soil

The state of water in the soil can be described in two ways: quantity present and energy status. The quantity present is expressed as gravimetric (mass) or volumetric. The gravimetric water content is the mass of water in a unit mass of dry soil (g of water/g of dry soil). The wet weight of soil sample is determined; the sample is dried at 105 ^{o} C to constant weight and reweighed (Gardner, 1986). The volumetric water content is expressed in terms of the volume of water per volume of soil (cm^3 of water/cm^3 of soil). Volumetric water content can be calculated from gravimetric water using the equation:

$$\theta v = \theta w^* \rho b \quad (1)$$

Where θv is the volumetric water content, θw is the gravimetric water content and ρb is the soil bulk density, which must be determined for the same soil under field conditions.

The energy status of water in soil can be expressed as follows (Hanks and Ashcroft, 1980):

$$\Psi_{total} = \Psi_{matric} + \Psi_{solute} + \Psi_{grav.} \quad (2)$$

Where Ψ_{total} is the total soil water potential (MPa), Ψ_{matric} soil matric potential (MPa), Ψ_{solute} soil solute potential (MPa) and Ψ_{grav} pressure potential or gravimetric water potential (MPa). The energy of water in the soil is attenuated by the hydrophilic surfaces of soil particles. As a result of the attraction of water to these surfaces, the energy of the water is decreased. Water forms films around the particles and fills pores. This fraction of the soil water energy is known as capillarity suction or matric water potential. The value of the matric term can be calculated from the capillarity rise equation:

$$\Psi_{matric} = -\rho_w gh = \frac{-2\gamma\cos(\alpha)}{r} \quad (3)$$

where, ρ_w is the density of water (kg m^{-3}), h = height of rise above a free water surface (m), g = acceleration due to gravity (m s^{-2}), γ = surface tension (N m^{-1}), α = wetting angle (degrees) and r = capillarity radius (m) (Hanks & Ashcroft, 1980; Hillel, 1980). The pressure potential is present in saturated soil due to the pressure of water above a given point and is calculated with the equation:

$$\Psi_{grav.} = \rho_w gh \quad (4)$$

where, ρ_w, g, and h were previously defined. The presence of solutes in the soil water further decreases its energy potential. The solute or osmotic potential of soil water is less than or equal to zero, and is directly related to the total solute concentration in the water, according to the following equation:

$$\Psi_{solute} = cRT \quad (5)$$

where, R is the universal gas constant (8.3143 J K^{-1} mol^{-1}), T is the absolute temperature and c is the osmolality of the solution. At low concentrations, where the activity coefficient is near 1, c is approximately equal to the total molar concentration of osmotically active species in the water.

For a given soil, there is a unique relationship between the soil water content and the soil water potential. This relationship is known as the soil water characteristic curve or soil water release curve (Klute, 1986). The curve derived by determining the energy status of water in the soil at several water contents may vary considerably with changes in soil texture (Figure 1)

Two approaches are used to obtain the relationship between soil water content and soil water potential. Either a given water content is first established, and the water potential then determined, or conditions are imposed on a soil sample to bring it to a given water potential, and the water content of the sample is determined after equilibrium is reached.

In the latter case, vacuum and pressure plate apparatus have been use extensively down to -1.5 MPa matric water potential (Klute, 1986). These are best applied where the soil solution is diluted and therefore the contribution of solutes to total water potential is minimal. In typical applications, moist soil samples are placed on a ceramic plate (down to -0.08 MPa) or a membrane (to -1.5 MPa), and a fixed suction or pressure is applied to a given potential until no more water is forced out of the sample. In practical terms, a vacuum can be applied to the ceramic plates down to potential of approximately -0.8 MPa. Below this potential, the soil samples must be housed in a pressure chamber to which constant air pressure can be applied; water is then force out of the soil sample and through the ceramic plate or membrane until no ore water is drained. At this point, it is assumed that the water potential of the remaining soil water is exactly equal to the negative of the pressure applied. This technique is used down to water potential of -1.5 MPa.

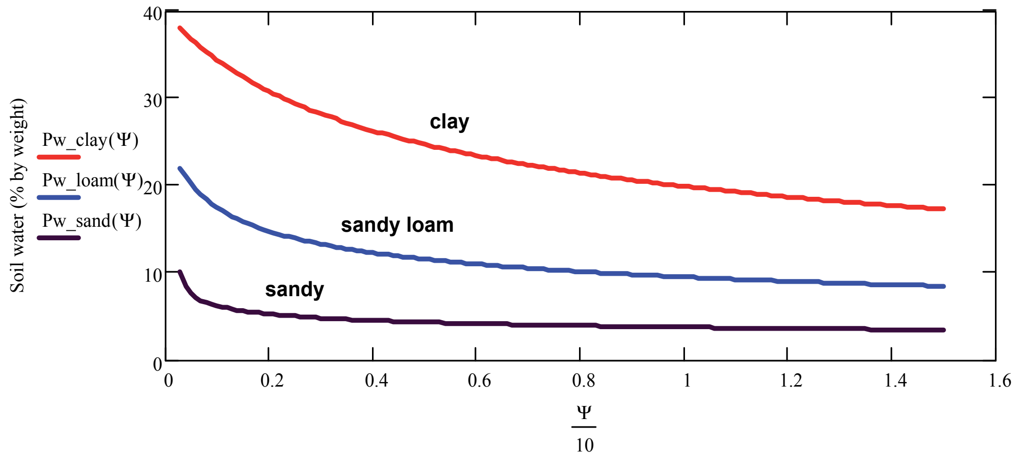


Fig. 1. Typical relationships between soil water content and soil water potential in clay, sandy loam and clay soils.

Psychrometric systems have been used to determine the total soil water potential of samples at different soil water contents. The relative humidity of air in equilibrium with the moist soil sample is determined, and expressed in terms of the corresponding water potential. If the soil is low in salts, only the matric potential is represented; otherwise, the sum of matric and osmotic potential results. Because relative humidity near 100% may be difficult to measure accurately, the psychrometric technique may be difficult to measure accurately, the psychrometric technique is best applied to systems where the soil water potential is less than -0.20 MPa. (Rundel & Jarrel, 1991)

2.1 Depth of available soil water

The Depth of total, depleted and residual available soil water can be calculated from the following equations:

$$TAW = [\theta_{w\_FC} - \theta_{w\_PWP}]*(\rho b/\rho w)*Z \qquad (6)$$

$$DAW = [\theta_{w\_FC} - \theta_{w\_actual}]*(\rho b/\rho w)*Z \qquad (7)$$

$$RAW = [\theta_{w\_actual} - \theta_{w\_PWP}]*(\rho b/\rho w)*Z \quad (8)$$

where, TAW=depth of total available soil water (cm), DAW= depth of depleted available soil water (cm), RAW= depth of residual available soil water (cm), θ_{w_FC} = gravimetric soil water content at field capacity (g/g), θ_{w_PWP} = gravimetric soil water content at permanent wilting point (g/g), θ_{w_actual} = gravimetric soil water content at the time of measurement (g/g), ρb = soil bulk density (g/cm^3), ρw = density of water (g/cm^3), Z = soil depth to irrigate (cm).

3. Gravimetric water content

Gravimetry refers to the measurement of soil water content by weighing. It is the oldest and most direct method, and when done carefully with enough samples is the standard against which other methods are calibrated and compared. This technique requires careful sample collection and handling to minimize water lose between the time is collected and weighed. Replicated samples at the same soil depth should be taken to reduce the inherent sampling variability that results from small volumes of soil. The equipment required includes a soil auger, sample collection cans, a balance accurate to at least 1 gram and a drying oven (Figure 2).

Fig. 2. Equipment used by the gravimetric technique for measuring soil water content.

The technique involves taking soil samples from each of several desired depths in the crop root zone and temporarily storing them in containers (water vapor-proof). The samples are then weighed and the opened containers oven-dried under specific time and temperature conditions (105 ^{o}C for 24 h). The dry samples are re-weighed. Percent soil water content on a dry mass or gravimetric basis, Pw is determined as:

$$Pw = \frac{WSW - DSW}{DSW} * 100 \quad (9)$$

where, WSW = wet sample weight (g), DSW = dry sample weight (g). The difference between wet and dry weight is the mass of water remove by drying. To convert from gravimetric basis to water content on a volumetric basis (Pv), multiply the gravimetric soil water content by the soil bulk density (ρb).

$$Pv = Pw * \rho b \tag{10}$$

Although the gravimetric method is relatively simple and inexpensive, it has several limitations. It is time-consuming and labor-intensive compared with other methods of soil moisture measurements, results are known after a minimum of 24 h after sampling, a large number of samples must be taken to remove the inherent variability of this approach. As it is a destructive technique, repeated measurements at the same point in the soil are not possible.

The use of microlysimeters is also a gravimetric method (Boast & Robertson, 1982) that allows repeated measurements at the same time, for a direct estimate of soil evaporation rate in additions to soil water content. The procedure consists in inserting into the soil a small piece of aluminum or PVC pipe (10 to 20 cm in diameter and length). Then the pipe and the enclosed soil are removed by carefully excavating around the perimeter. The pipe is sealed on the bottom, weighed, then placed in a plastic bag and replaced in the same position in the soil, with the plastic bag pulled back to exposure the soil surface to the atmosphere. The soil surrounding the microlysimeter is repacked to resemble the original surface as closely as possible. At a later time the microlysimeter can be removed and reweighed to determine the water loss (soil surface evaporation) during the intervening time period. This may be done several times, after which the soil can be oven-dried and reweighed to back-calculate water content at each weighing. This is an inexpensive, direct and reasonably accurate measurement of soil evaporation (Lascano & van Bavel, 1986), but it is time-consuming and labor intensive. Since the soil in the core is not in hydraulic contact with the soil below, the evaporation rate form the core will eventually diverge from that of the surrounding soil, so a given core should not be used for more than a few days.

4. Neutron scattering

Neutron scattering is a time-tested indirect determination of soil water content. This method estimates the amount of water in a volume of soil by measuring the amount of hydrogen atoms present. A neutron probe consists of a source of fast or high energy neutrons and a detector, both housed in a unit which is lowered into an access tube installed in the soil. The probe is connected by a cable to a control unit located in the soil surface. Clips on the cable allow the cable to be set at pre-selected depths into the soil profile. Access tubes should be installed to the depth of the expected growth of the root crop. The control unit includes electronics for time control, a counter, memory and other electronics for processing readings (Figure 3).

This technique works based on the following principle. Fast neutrons emitted from the interaction of a radioactive alpha-emitter with Beryllium, pass through the access tube into the surrounding soil, where they gradually lose energy by collision with other atomic nuclei. Hydrogen atoms in the soil (mostly in water molecules) are effective in slowing the fast neutrons because they are of approximately the same mass. The result is a cloud of slow or thermalized neutrons; some of them diffuse back to the detector. The size and density of the cloud depends mainly on soil type and soil water content, and is spherical in shape (Figure 4) with a diameter of 15 to 40 cm. Thermalized neutrons that impact the detector create a small electrical impulse, which is amplified and counted. The number of slow neutrons counted in a specified interval of time is linearly related to the total volumetric soil water content. A higher count indicates higher soil water content.

Fig. 3. Neutron probe for measuring soil water content.

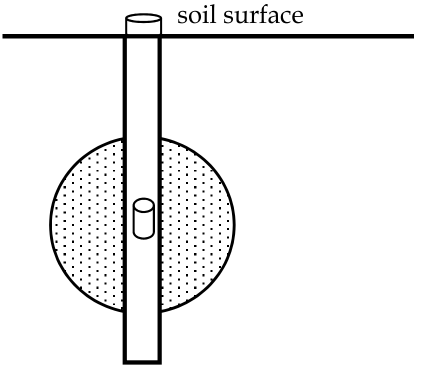


Fig. 4. Spatial sensitivity of neutron scattering in the soil.

Commercial neutron probes combine the source and detector in a single unit which fits in the access tube. They also include a standard material within the housing, so that a standard count may be taken prior to each measurement. This allows expressing the reading as count ratio (count in the soil/count in the standard), to account for changes in source strength associated with radioactive decay and for instrument drift.

Neutron probe must be calibrated for the soil type in which they will be used (Baker, 1990). Manufacturers provide a calibration curve with each neutron prove, but it is probably useful only for moisture measurements in homogeneous sands and gravels. Several studies have shown that factory-supplied curves give large errors when used in agricultural soils (Chanasky & McKenzie, 1986). Soil-specific calibration is necessary because detector readings are affected by the presence of non-water hydrogen (principally in organic matter), other elements in the soil with the ability to thermalized fast neutrons, and elements that absorb fast neutrons such as boron, cadmium and chlorine. The calibration procedure consists on compare neutron count ratios taken in a defined soil depth, against water content determined gravimetrically from samples taken nearby at the same soil depth.

The neutron probe allows relatively rapid and repeatable measurements of soil water content to be made at several depths and locations within a field. Repeatable measurements at the same location through the crop growing season, reduces the effect of soil variability on the measurements.

The main advantages of this method are: direct reading of soil water content, large volume of the soil is sampled, one unit can be used in several locations, and is accurate when properly calibrated. The main disadvantages are: individual calibration for each type of soil is required, difficult to use in automatic monitoring, its use near the surface requires spatial technique because of the escape of fast neutrons, and the high cost of the unit. There is also a radiation safety hazard, which requires special licensing, operation training, handling, shipping and storage procedures.

Example 1:

A homogeneous and deep soil has the following parameters: θ_{w_FC} =0.285 g/g, θ_{w_PWP} = 0.140 g/g, ρ_b = 1.25 g cm^{-3}. The calibration equation of the neutron probe used to measure soil water content was: θ_w = -0.031 + 0.1496*C.R, where θ_w is the gravimetric water content (g/g) and C.R. is the counting ratio of the thermalized neutrons. If the neutron probe gave a reading of 1.452 in a soil depth of 40 cm, determine: depth of total available soil water (TAW), depth of depleted available soil water (DAW) and depth of residual available soil water (RAW). Assume that the density of water is 1 g/cm^3.

TAW is calculated using equation (6):

$$TAW = [\theta_{w\_FC} - \theta_{w\_PWP}]*(\rho b/\rho w)*Z$$

Substituting values in the above equation we get:

$$TAW = [0.285 - 0.140]*(1.25/1.0)*40 = 7.25 \text{ cm of water}$$

To calculate the depleted and residual available soil water, the soil water content at the time of measurement must be first calculated, using the calibrated equation of the neutron probe:

$$\theta_w = -0.031 + 0.1496*C.R$$

$$\theta_w = -0.031 + 0.1496*(1.452)$$

$$\theta_w = 0.186 \text{ g/g}$$

Similarly, DAW is calculated with equation (7):

$$DAW = [\theta_{w\_FC} - \theta_{w\_actual}]*(\rho b/\rho w)*Z$$

By substituting values we obtain:

$$DAW = [0.285 - 0.186]*(1.25/1.0)*40 = 4.95 \text{ cm of water}$$

RAW is calculated using equation (8)

$$RAW = [\theta_{w\_actual} - \theta_{w\_PWP}]*(\rho b/\rho w)*Z$$

Substituting values:

$$RAW = [0.186 – 0.140]*(1.25/1.0)*40 = 2.30 \text{ cm of water}$$

5. Tensiometers

Soil water tension, soil water suction or soil water potential are all terms describing the energy status of soil water. Soil water potential is a measure of the amount of energy with which water is held in the soil. A water release curve shows the relation between soil water content and soil water tension.

Tensiometers have been used for many years to measure soil water tension in the field. Tensiometers are water-filled tubes with a ceramic cup attached at one end and a vacuum gauge (or mercury manometer) airtight seal on the other end. The device is installed in the soil with the ceramic cup in good contact with the surrounding soil at the desired depth (Figure 5). The soil matric potential is measured by the vacuum gauge as water is pull out of the ceramic cup into the soil by matric forces. As the soil is rewetted, the tension gradient reduces and water flows into the ceramic cup. As the soil goes through wetting and drying cycles, tension readings can be taken.

Fig. 5. Use of tensiometers to determine soil matric potential at different soil depths.

Commercially available tensiometers use a vacuum gauge to read the tension in a scale from 0 to 100 kPa, although the practical operating range is from 0 to 70 kPa, because once air enters the tube, values are no longer accurate. If the water column is intact, a zero reading indicates saturated soil conditions. Readings of about 10 kPa correspond to field capacity for coarse-textured soils, while readings of around 30 kPa can approximate field capacity for fine-textured soils.

Tensiometer readings can be used as indicators of soil water content and the need for irrigation. When instruments installed at the active root zone of a given crop, reach a certain reading, they can be used to indicate when to start irrigation, based on soil texture and soil type. Similarly, instruments at deeper depths of the root zone may be used to indicate when adequate water has been applied. However, to determine the depth of water to applied, the curve that relates soil water content against soil water potential for the specific soil must be known.

Careful installation and maintenance of tensiometers is required for reliable results. The ceramic cup must be in intimate and complete contact with the soil. A few hours to a few days are required for the tensiometer to come to equilibrium with the surrounding soil. The tensiometer should be pumped with a hand vacuum pump to remove air bubbles. The length of the tensiometers is from 15 to 120 cm. It is recommended that the tensiometers be installed in pairs, one at 1/3 and the other at 2/3 of the crop rooting depth. They should be installed out of the way of traffic and cultivation. In freezing climates, insulate or remove tensiometers during winter months, because it takes only a small frost to knock the vacuum gauges out of calibration.

Tensiometers have been used to estimate water balance (Devitt *et al*., 1983), follow capillarity rise above the water table (McIntyre, 1982) and characterize unsaturated soil hydraulic conductivity (Ward *et al*., 1983). More recently, Zermeño-Gonzalez *et al.* (2007) used tensiometers to schedule irrigation in an orchard of lemon. They found that the highest fruit yield can be obtained when irrigation is applied at a reading of 30 kPa of tensiometers installed at a soil depth of 30 cm.

The main advantages of this method are: direct reading of soil water matric potential, inexpensive, automatic for continuous reading, relatively reliable. The main disadvantages are: requires the soil moisture characteristic curve to relate to soil water content, samples a small portion of soil near the cup may take a long time to reach equilibrium with the soil.

Example 2:

Zermeño-González *et al.* (2007) obtained a calibration equation to get soil moisture content as a function soil tension measured with a tensiometer installed at a soil depth of 30 cm. The equation was: L = 109.30 – 17.29*ln(Tens), where, L is the soil water content at a depth of 30 cm (mm/30 cm), Tens is the soil water tension (kPa). If the reading of the tensiometer was 40 kPa, determine the depth of water to be applied to take the soil water content to field capacity, assuming that for that soil and crop (an orchard of lemon) a soil water tension of 15 kPa corresponds to field capacity.

The depth of water to be applied to take the soil water content to field capacity can be calculated with the following relation:

$L_{\_to\_FC} = L_{15kPa} - L_{actual\_kPa}$ where: L_{15kPa} is the soil water content at 15 Kpa (mm/30 cm) and L_{actual_kPa} is the soil water content that corresponds to the actual reading of the tensiometer (mm/30 cm). substituting the calibration equation in this relation we obtain:

$$L_{\_to\_FC} = [109.30 - 17.29*Ln(15)\,] - [109.30 - 17.229*Ln(40)]$$

$$L_{\_to\_FC} = [62.478 \text{ mm}] - [45.519 \text{ mm}]$$

$$L_{\_to\_FC} = 16.959 \text{ mm/30 cm}$$

6. Porous blocks

Porous blocks are made of materials such as gypsum, ceramic, nylon and fiberglass. Similar to tensiometers, the blocks are buried in intimate contact with the soil at some desired depth and allowed to come to water tension equilibrium with the surrounding soil. Once equilibrium is reached, different properties of the block which are affected by water tension may be measured.

One of the more common types of porous blocks are electrical resistance blocks. Electrodes inside the block are used to measure the resistance to electrical current flow between them. In operation, measurements are made by connecting an ohmmeter to the electrodes of the resistance block. The resistance is proportional to the quantity of water in the block, which is a function of soil water tension. Higher resistance readings mean lower block water content and thus higher soil water tension. By contrast, lower resistance readings indicate higher block water content and lower soil water tension. A Useful technique is to calibrate blocks in soil on a pressure plate apparatus. In this way, resistance, water content and soil water potential can be determined simultaneously on each sample.

Resistance blocks work best in soils drier than -0.05 MPa, making the complementary in the range of operation to soil tensiometers. They are typically accurate to soil matric potentials as low as -2.0 to -3.0 MPa. Because response time of resistance blocks is slow, they are not useful for following rapid wetting events. Significant hysteresis effect may also be found between wetting and drying calibrations. Gypsum blocks require little maintenance and can be left in the field under frizzing conditions. Being made of gypsum, the block will slowly dissolve, requiring replacement. The rate of dissolution depends on soil pH and soil water conditions. Gypsum blocks are best suited for use in fine-textured soils. They are not sensitive to changes of soil water tension from 0 to 100 kPa. High soil salinity affects the electrical resistivity of the soil solution, although the gypsum buffers this effect to a certain degree.

Watermark blocks or granular matrix sensor, is a new style of electrical resistance block. The electrodes are embedded in a granular matrix material, similar to compressed fine sand. A gypsum wafer is embedded in the granular matrix near the electrodes. A synthetic porous membrane and a PVC casing with holes hold the block together. The granular matrix material enhances the movements of water to and from the surrounding soil, making the block more responsive to soil water tensions in the range from 0 to 100 kPa. These sensors have good sensitivity to soil water tension in a range of 0 to 200 kPa. This makes them more adaptable to a wide range of soil textures and irrigation regimes than gypsum blocks and tensiometers.

Readings are taken by attaching special electrical resistance meter to the wire leads and setting the estimated soil temperature. The readings of the Watermark meter are kPa of soil water tension, similar to the tensiometers. Watermark blocks require little maintenance and can be left in the soil under frizzing conditions. The blocks are much more stable and have a longer life than gypsum blocks. Soil salinity affects the electrical resistivity of the soil water solution and may cause erroneous readings. The gypsum wafer in the watermark blocks offers some buffering of this effect.

The main advantages of resistance blocks are: they are calibrated for soil water potential, are reliable, inexpensive, can be automated for monitoring. Disadvantages: requires the soil moisture characteristic curve to relate to water content, must be calibrated individually, and samples a small volume of soil.

Example 3:

At the agricultural experimental station of Universidad Autonoma Agraria Antono Narro, in Saltillo, Coahuila, Mexico, a Watermark block was calibrated against gravimetric measurements in a clay loam soil. The calibration was performed at a soil depth of 30 cm where the bulk density was 1.206 g cm^3. Determine the depth of available soil water between 20 and 100 kPa, for a soil depth of 30 cm.

The calibration equation of the Watermark block was:

$$\theta w = 0.215 - 0.0005{*}Tens$$

$$R^2 = 0.853$$

Where: θw is the gravimetric water content (g/g), Tens is the soil water tension (kPa).

The depth of available soil water (AW) between two gravimetric soil water contents can be calculated with the following equation:

$$AW = [\theta_{w1} - \theta_{w2}]{*}(\rho b/\rho w){*}Z \quad (11)$$

where, θ_{w1} is the initial or higher gravimetric soil water content (g/g), θ_{w2} is the final or lower gravimetric soil water content (g/g) the other variables of equation (10) were previously defined. θ_{w1} and θ_{w2} are calculated by substituting 20 and 100 kPa respectively in the calibration equation of the Watermark block

$$\theta_{w1} = 0.215 - 0.0005{*}Tens$$

$$\theta_{w1}1 = 0.215 - 0.0005{*}(20)$$

$$\theta_{w1} = 0.205 \text{ g/g}$$

$$\theta_{w2} = 0.215 - 0.0005{*}Tens$$

$$\theta_{w2} = 0.215 - 0.0005{*}(100)$$

$$\theta_{w2}2 = 0.165 \text{ g/g}$$

Finally, substituting the value of : θ_{w1} and θ_{w2} in equation (10) the depth of available soil water is obtained:

$$AW = [\theta_{w1} - \theta_{w2}]{*}(\rho b/\rho w){*}Z$$

$$AW = [0.205 - 0.165]{*}(1.206/1.00){*}30$$

$$AW = 1.447 \text{ cm}; = 14.47 \text{ mm}/30 \text{ cm}$$

7. Time domain reflectometry

Time-domain reflectometry (TDR) is a method for measuring soil water content, based in the determination of the dielectric permittivity of the porous media at microwave (MHz-

GHz) frequencies. The method uses equipment developed for testing coaxial cables in the telecommunications industry, which consists of a pulse generator, a sampler that produces a low frequency facsimile of high frequency signals, and an oscilloscope that displays the sampler output. Electromagnetic pulses of frequencies in the 1 MHz to 1 GHz region are sent down to a coaxial transmission line that ends in a parallel pair of stainless steel rods embedded in the soil. The unit samples and displays the reflected pulses, which exhibit perturbations at any point in the transmission line where impedance changes occur, as happens at the juncture of the cable with the steel waveguides. The termination of the transmission line at the end of the waveguides is also clearly visible on the oscilloscope since the remaining energy in the pulse is reflected at that point. The distance on the oscilloscope screen between these two points together with the known length of the waveguides allows calculation of the pulse propagation velocity (Vp), relative to the velocity of electromagnetic radiation in a vacuum ($c=3*10^8$ m s^{-1}). From this relation the apparent dielectric permittivity (Ka) can be approximated by the equation:

$$Ka = \left(\frac{c}{Vp}\right)^2 \tag{12}$$

The apparent dielectric permittivity of the soil depends on the volume fraction of the soil constituents and their respective dielectric permittivity. Ka of the dry minerals of the soils varies between 2 and 5, the air has a Ka of 1 while the Ka of water is approximately 80. This shows that Ka for the soil is strongly dependent on soil water content. Topp et al. (1980) found that a third order polynomial equation best fit the data between volumetric water content (θv) and the apparent dielectric permittivity of the soil (Ka), over the range of water content from air-dry to saturation.

$$\theta v = -5.3 * 10^{-2} + 2.92 * 10^{-2} Ka - 5.5 * 10^{-4}\, Ka^2 + 4.3 * 10^{-6}\, Ka^3 \tag{13}$$

Equations 12 and 13 show that the apparent dielectric permittivity of the soil is inversely related to the pulse propagation velocity, i.e., faster propagation velocity indicates a lower dielectric permittivity of the soil and thus lower soil water content. Or, as soil water content increases, propagation velocity decreases, and the dielectric permittivity of the soil increases.

Waveguides inserted into the soil consist of a pair of parallel stainless steel rods spaced between 3 and 5 cm apart. They can be installed in the soil horizontally, vertically at an angle of 45^o etc. The TDR soil water measurement system measures the average volumetric soil water content along the length of the waveguide. The volume of soil sampled approximates a cylinder surrounding the waveguide with a diameter about 1.5 times the spacing of the parallel rods.

The waveguides may be permanently installed with wire leads brought to the surface, but this requires care to minimize soil disruption. Horizontal installation yields a depth-specific measurement, while insertion at a 45^o angle integrates a larger volume of soil horizontally and vertically. Portable hand push waveguide probes can be used to measure at different locations in the upper soil profile which corresponds to the length of the waveguides. Waveguide must be carefully inserted into the soil with full soil contact along the entire length of the rods. Annular air gaps around the rods will affect readings of the low side. The waveguide rods must remain parallel when they are installed in the soil.

Once properly calibrated and installed, the TDR technique is highly accurate. Precise measurements may be made near the surface, which is an important advantage compare to other techniques such as the neutron probe. Research has shown (Evett *et al*., 2001; Pedro-Vaz & Hopmans, 2001) that the dielectric permittivity of the soil is nearly independent of soil type and bulk density and relatively unaffected by soil salinity. Soil salinity or bulk electrical conductivity affects the degree of attenuation of electromagnetic pulse in the soil. Other studies (Jacobsen & Schjonning, 1993) found that inclusion of soil bulk density, clay and organic matter content in the calibration equation improves the correlation, suggesting that complex interactions between the soil components affect the electric properties of the soil.

The CS616 TDR probe (Campbell, Sci., Inc, USA) (Figure 6) consists of two stainless steel rods connected to a printed circuit board. A shielded four-conductor cable is connected to the circuit board to supply power, enable the probe, and monitor the pulse output. The circuit board is encapsulated in epoxy. High-speed electronic components on the circuit board are configured as a bistable multivibrator. The output of the multivibrator is connected to the probe rods which act as a waveguide.

The fundamental principle of CS616 operation is that an electromagnetic pulse will propagate along the probe rods at a velocity that is dependent on the dielectric permittivity of the material surrounding the rods. As water content increases, the propagation velocity decreases because polarization of water molecules takes time. The travel time of the applied signal along 2 times the rod length is essentially measured. The applied signal travels the length of the probe rods and is reflected from the rod ends traveling back to the probe head. A part of the circuit detects the reflection and triggers the next pulse. The Water Content Reflectometer output is essentially a square wave with an amplitude of +/- 0.7 volts and a period that fluctuates between 16 and 32 μs, which depends on the volumetric water content and is used for the calibration equation. For soil solution electrical conductivity values less than 2 dS m^{-1} The calibration equation is: $\theta v = -0.0663-0.0063*t+0.0007*t^2$, where θv is he volumetric soil water content (m^3/m^3) and t is the period of the square wave (μs).

Fig. 6. CS616 TDR probe for measurement of volumetric soil water content.

The main advantages of this method are: measures water content, samples large soil volume therefore decreases interference due to heterogeneity, can be automated for continuous readout, relatively stable over time. The main disadvantages are: Insertion of rods may be difficult, may sample excessively large soil volume, and requires the use of a datalogger.

Example 4:

A CS616 was used to measure the soil water content of the upper 30 cm of the soil profile in a soya bean crop. If the reading of the probe was 28 μs one day-after irrigation, and 25 μs seven days later, determine the crop evapotranspiration if no rain was observed during the TDR readings.

The volumetric water content one day after irrigation was:

$$\theta v\_1= -0.0663-0.0063*(28)+0.0007*(28)^2$$

$$\theta v\_1= 0.306\ m^3/m^3$$

and 7 days later:

$$\theta v\_7= -0.0663-0.0063*(25)+0.0007*(25)^2$$

$$\theta v\_7= 0.214\ m^3/m^3$$

The crop evapotranspiration (LamET) was the difference in volumetric water content during the seven days multiplied by the soil depth

$$LamET = (\theta v\_1- \theta v\_7)*Soil\_depth$$

$$LamET = (0.306-0.214)*0.30$$

$$lamET = 0.0276\ m$$

$$LamET = 27.6\ mm$$

The average daily crop evapotranspiration (LamETprom) during the seven days was:

$$LamETprom = 27.6/7 = 3.943\ mm$$

8. Impedance and capacitance methods

The Impedance and capacitance as well as the TDR techniques are electromagnetic (EM) sensors, which principle is based in the significant difference in the dielectric permittivity (Ka) between water, air and mineral particles of the soil. Therefore, is possible to establish a good relation between the soil water content ($m^3\ m^{-3}$) and Ka, such as the Topp equation (Equation 12), (Topp *et al*., 1980).

EM sensors determine Ka of an unsaturated porous medium from different physical principles; transit time, impedance, capacitance, etc. For instance, the TDR (Time Domain Reflectometry) and TDT (Time Domain Transmission) techniques estimate Ka from the relationship between this and the transit time (ts) of an electromagnetic wave travelling along the rods of length L of a probe inserted into a porous medium, according to the following equation (Campbell, 1990):

$$Ka = \frac{(ts*c)^2}{(2*L)^2} \tag{14}$$

where, c is the speed of light (m/s) in the vacuum.

Impedance sensors determine the amplitude difference in voltage due to changes in impedance, Z (Ω), between the transmission line of the sensor and the rods that are inserted in the porous media, using the equation (Kelleners *et al.*, 2005):

$$\sqrt{ka} = \frac{c*InvCotan(Z(\Omega))}{2*\pi*L} \tag{15}$$

Capacitance methods, consider the composite media soil-probe as a capacitor whose capacitance, C (F), is proportional to Ka, according to the following equation:

$$C(F) = g(m)*Ka*Ko \tag{16}$$

where, g(m) is a geometric factor and Ko =8.54 is the value of permittivity of the vacuum. The relation obtained between Ka or θ and the signal provided by a given EM sensor is known as the calibration equation. In general, the manufacturer of a specific EM sensor provides signal versus θ equations or signal versus Ka, valid for some conditions of media or soil type. However, because the soil is a heterogeneous porous medium of variable composition and since Ka depends on other variables such as the electrical conductivity of the medium or the frequency of the EM wave, It is recommended to perform a recalibration of the manufacturer equation of the sensor, especially when a more accurate determination of the soil water content is required.

Regalado *et al*. (2010) made a recalibration of the manufacturer equation of nine RM sensors. For the EC10 and EC20 capacitance probes of Decagan Devices, Inc, the manufacturer equations were:

$$\theta v = -0.376+ 9.36*10^{-4} *S \tag{17}$$

and,

$$\theta v = -0.290 + 6.95*10^{-4}*S \tag{18}$$

The ML2x impedance probe of Delata –T devices Ltd., the manufacturer equation was:

$$Ka^{0.5} = 1.07+6.40*10^{-3}*S- 6.40*10^{-6}*S^2+4.7*10^{-9}*S^3 \tag{19}$$

where S is the reading signal of the sensor (mv).

After recalibration in a non saline solution of different values of dielectric permittivity (Ka), the new equations for the EC10 and EC20 capacitance probes were:

$$1/Ka = 0.0589/S^2 – 0.0455 \tag{20}$$

$$1/Ka = -0.2581 +0.0607*S + 0.2331/S \tag{21}$$

And for the impedance probe was:

$$1/Ka = 0.134/S^{0.5} - 0.105 \quad (22)$$

They also concluded that after recalibration, all sensors behaved correctly under conditions equivalent to those of a non saline soil with sandy texture. Since the sensors studied performed acceptable for the entire range of water content, its suitability for a particular application should be decided according to other specific criteria such as volume of soil explored, robust probes, possibility of automation of the readings, cost, etc.

9. Conclusions

Understanding the soil water holding capacity and the factors affecting the plant available soil water are necessary for good Irrigation management. Adequate soil moisture is critical to plant growth. Too little water, or water applied at the wrong time, causes stress and reduces growth and too much may result in surface runoff, erosion and leaching of nutrients and pesticides.

Different techniques are currently available to directly measure or determine soil water content in a discrete or continuous manner. Some are very simple and others are more complex techniques. The cost of keeping track of soil water content is paid back through the benefits of effective water management, such as energy savings, water savings, water quality improvement, and improvement in quality and yield of harvest.

Successful implementation of any of the methods requires careful attention during the installation, operation, and maintenance of the equipment and sensors. Soil type, soil salinity and irrigation regime are important parameters that must be considered to choice a particular method or technique to get the best results. A routine sampling schedule should be implemented to obtain the most information from any of these methods. The difference in soil water content at a given location from one sampling time to the next often provides more information than random space and time measurements. Soil water should be measured or monitored in at least two depths in the active crop root zone at several locations in a field to obtain a field average.

There have been many advances in electromagnetic (EM) sensor technology (time domain reflectometry (TDR, impedance and capacitance-based approach) which have resulted in sensors that are more robust, less expensive, more suitable for different soil types that can be connected to advanced data loggers for a continuous monitoring of soil water content. Real-time, continuous measurement of soil moisture in the plant rooting zone is very important for determining crop evapotranspiration and the amount of water to apply.

10. References

Baker, J.M. (1990). Measurem Pearcy, R.W., Ehleringer, J., Mooney, H.A. & Rundel, P.W ent of soil water content. *Remote Sensing Reviews* 5(1):263-279.

Boast, C.W. & Robertson, T.M. (1982). A "micro-lysimeter" method for determining evaporation from bare soil: description and laboratory evaluation. *Soil Sci. Soc. Am. J.* 46:689-696.

Campbell, J.E. (1990). Dielectric properties and influence of conductivity in soils at one to fifty megahertz. *Soil Sci. Soc. Am. J.* 54: 332-341.

Chanasky, D.S. & McKenzie, R.H. (1986). Field calibration of a neutron probe. *Ca. J. Soil Sci.* 66:173-176.

Devitt, D., Jurry, W.A., Sternberg, P. & Stolzy, L.H. (1983). Comparison of methods used to estimate evapotranspiration for leaching control. *Irrig. Sci.* 4:59-69.

Evett, S. Laurent, J-P., Cepuder, P. & Hignett, C. (2001). Neutron scattering, capacitance, and water TDR soil water content measurements compared on four continents. *Proceedings of the 17th World Congress of soil Sci.*, 14-21 august, Thailand.

Gardner, W.H. (1986). Water Content. In: *Methods of Soil Analysis, Part 1. Amer. Soc. Agron*. Madison, WI. Pp 493-544.

Hanks, R.J. & Ashcroft, G.L. (1980). *Applied Soil Physics*, Springer-Verlag, Berlin, 159 p.

Hillel, D. (1980). Fundamentals of Soil Physics, Academic Press, new York, 413 p.

Jacobsen, O.H. & Schjonning. (1993). A laboratory calibration of time domain reflectometry for soil water measurement including effects of bulk density and texture. *Journal of Hydrology* 151(2-4):147-157.

Kelleners, T.J., Robinson, D.A., Shouse, P.J., Ayars, J.E. & Skaggs, T.H. (2005). Frequency dependence of the complex permittivity and its impact on dielectric sensor calibration in soils. *Soil Sci. Soc. Am. J.* 69: 67-76.

Klute, A. (1986). Water retention: laboratory methods . In: *Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods*, 2nd edn, Agronomy Number 9 (Part 1), (ed. A. Klute), *American Society of Agronomy*, Madison,pp. 635-662, ISBN 0-89118-088-5

Lascano, R.J. & van Bavel, C.H.M. (1986). Simulation and measurement of evaporation from a bare soil. *Soil Sci. Soc. Am. J.* 50:1127-1133.

McIntyre, D.S. (1982). Capillary rise from saline groundwater in clay soil cores. *Aus. J. Soil. Res.*, 20: 305-313.

Regalado, C.M., Ritter, A. &Garcia, O. (2010). Dielectri response of commerial capacitance, impedance, and TDR electromagnetic sensors in standard liquid media, *proceedings of the third international symposium on soil water measurement using capacitance, impedance and TDT*, Murcia, Spain, april 2010.

Rundel, P.W. & Jarrel, W.M. (1991). *Water in the environment, In: Plant physiological ecology, field methods and instrumentation*, Pearcy, R.W., Ehleringer, J., Mooney, H.A. & Rundel, P.W, pp (29-56), Chapman and Hall, ISBN: 0-412-40730-2, London ,England.

Pedro-Vaz, C.M. & Hopmans, J.W.C. (2001). Simultaneous measurements of soil penetration resistance and water content with a combined penetrometer-TDR moisture probe, *Soil Sci. Soc. Am. J.* 65(1):4-12.

Topp, G.C., Davis, J.L. & Annan, A.P. (1980). Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resour. Res.*16:574-582.

Ward, A., Wells, L.G. & Philips, R.E. (1983). Characterizing unsaturated hydraulic conductivity of Western Kentucky surface-mine spoils and soils. *Soil Sci. Soc. Am. J.* 47:847-854

Zermeño-González, A., García-Delgado, M.A., B.I. Castro-Meza, B.I. & Rodríguez-Rodríguez, H. (2007). Tensión de humedad del suelo y rendimiento de fruto en limón Italiano. *Revista Fitotecnia Mexicana*, 30(3): 295-302

11

Precision Irrigation: Sensor Network Based Irrigation

N. G. Shah[1] ancd Ipsita Das[2]
[1]CTARA, IIT Bombay
[2]Department Of Electrical Engg, IIT Bombay
India

1. Introduction

Availability of water for agriculture is a global challenge for the upcoming years. This chapter aims at describing components of precision irrigation system and its potential in future farming practices. A case-study of deploying Wireless Sensor Network (WSN) monitoring soil moisture, estimating Evapotranspiration (ET) and driving drip irrigation for a large grape farm in India on pilot basis is described.

Agriculture plays a vital role in the economy of every nation be it developing or developed. Agriculture is the basis of livelihood for the population through the production of food and important raw materials. Moreover, agriculture continues to play an important role in providing large scale employment to people. Agricultural growth is considered necessary for development and for a country's transformation from a traditional to a modern economy. Therefore attention must be accorded to science and technology being used in the field for higher yield and growth in agriculture.

Agriculture system is a complex interaction of seed, soil, water, fertilizer and pesticides etc. Optimization of the resources is essential for sustainability of this complex system. Unscientific exploitation of agricultural resources to bridge the gap in supply/demand owing to the population growth is leading to resource degradation and subsequent decline in crop yields (Mondal and Tiwari, 2007). In addition, uncertainty of climatic conditions is also playing an important role in this complex system. This calls for optimal utilization of the resources for managing the controlled agricultural system (Whelan et al., 1997). Also agricultural systems are inherently characterized by spatial and temporal variability making yield maximization with minimal inputs a complex task. Thus the farming technologies followed in all parts of world need to be constantly updated to meet these challenges. Development of a range of new technologies in different parts of the world has brought agriculture to a whole new level of sophistication. In fact, modern agriculture has already undergone a sea-change from the ancient times. The concept of precision agriculture has been around for some time now. A new approach of collecting real time data from the environment could represent an important step towards high quality and sustainable agriculture. Precision agriculture is an agricultural system that can contribute to the sustainable agriculture concepts.

1.1 Precision Agriculture (PA)

The term "precision agriculture" is defined as the application of various technologies and principles to manage spatial and temporal variability associated with all aspects of agricultural production (Pierce and Nowak, 1999). Conventional agronomic practices always follow a standard management option for a large area irrespective of the variability occurring within and among the field. For decades now, the farmers have been applying fertilizers based on recommendations emanating from research and field trials under specific agro-climatic conditions (Ladha et al., 2000). Applications of agricultural inputs at uniform rates across the field without taking in-field variations of soil and crop properties into account, does not give desirable crop yield. Consideration of in-field variations in soil fertility and crop conditions and matching the agricultural inputs like seed, fertilizer, irrigation, insecticide, pesticide, etc. in order to optimize the input or maximizing the crop yield from a given quantum of input, is referred to as Precision Agriculture (PA). It is an information-based and technology-driven agricultural system, designed to improve the agricultural processes by precisely monitoring each step to ensure maximum agricultural production with minimized environmental impact. It involves the adjustment of sowing parameters, the modulation of fertilizers doses, site-specific application of water, pesticide and herbicides, etc (Adams et. al., 2000). Irrigating farms backed-up by estimated water-requirements is one of the essential components of precision agriculture to reduce water wastage. Given the limited water resources, optimizing irrigation efficiency is very essential.

1.2 Precision irrigation

Water plays a crucial role in photosynthesis and plant nutrition. The problem of agricultural water management is today widely recognized as a major challenge that is often linked with development issues. Agriculture consumes 70% of the fresh water i.e. 1,500 billion m^3 out of the 2,500 billion m^3 of water is being used each year (Goodwin and O'Connell 2008). It is also estimated that 40% of the fresh-water used for agriculture in developing countries is lost, either by evaporation, spills, or absorption by the deeper layers of the soil, beyond the reach of plants' roots (Panchard et. al., 2007). Post green-revolution era agriculture in India is facing a technological fatigue for two reasons viz a) high rates of ground-water depletion and b) soil salinity due to excessive irrigation in some pockets. Efficient water management is a major concern in many crop systems. More and more planners as well as farmer associations are becoming conscious about warder-audit and water utilization efficiency as the water resources is getting more and more scarce. Efforts of using micro-irrigation methods such as sprinkler and drip irrigation have been made in last three decades in many parts of the world. It has been reported that in year 2005, 1.15 million ha was under micro-irrigation (drip and sprinkler) in India (Modak, 2009). There is no ideal irrigation method available which may be suitable for all weather conditions, soil structure and variety of crops cultures. In the semi-arid areas of developing countries, marginal farmers and small farmers (with a land holding between 2 and 4 hectares) who cannot afford to pay for powered irrigation, heavily depend on the rainfall for their crops. It is observed that farmers have to bear huge financial loss because of wrong prediction of weather and incorrect irrigation method. In light of a real need to improve the efficiency of irrigation systems and prevent the misuse of water, the focus is to develop an intelligent irrigation scheduling system which will enable irrigation farmers to optimize the use of water and only irrigate where and when need for as long as needed.

Precision irrigation is worldwide a new concept in irrigation. Precision irrigation involves the accurate and precise application of water to meet the specific requirements of individual plants or management units and minimize adverse environmental impact. Commonly accepted definition of Precision irrigation is sustainable management of water resources which involves application of water to the crop at the right time, right amount, right place and right manner thereby helping to manage the field variability of water in turn increasing the crop productivity and water use efficiency along with reduction in energy cost on irrigation. It utilizes a systems approach to achieve 'differential irrigation' treatment of field variation (spatial and temporal) as opposed to the 'uniform irrigation' treatment that underlies traditional management systems.

1.2.1 Benefits of precision irrigation

Precision irrigation has the potential to increase both the water use and economic efficiencies. It has been reported that precision irrigation (Drip and Sprinkler) can improve application efficiency of water up to the tune of 80-90% as against 40-45% in surface irrigation method (Dukes, 2004). Results from case studies of variable rate irrigation showed water savings in individual years ranging from zero to 50%. The potential economic benefit of precision irrigation lies in reducing the cost of inputs or increasing yield for the same inputs.

1.2.1.1 Water savings

The primary goal of precision irrigation is to apply an optimum amount of irrigation throughout fields. It is reported by many researchers as the most likely means of achieving significant water savings (Evans and Sadler, 2008). The site specific or variable rate irrigation is considered as a necessary or essential component of precision irrigation. Most researchers expect a reduction in water use on at least parts of fields, if not a reduction in the value aggregated over entire fields (Sadler *et al.* 2005). It has been reported that variable rate irrigation could save 10 to 15% of water used in conventional irrigation practice (Yule *et al.* 2008). Hedley and Yule (2009) suggested water savings of around 25% are possible through improvements in application efficiency obtained by spatially varied irrigation applications.

1.2.1.2 Yield and profit

The experimental studies were carried out by King *et al.* (2006) for measuring the yield of potatoes under spatially varied irrigation applications. It was reported that yields were better in two consecutive years over uniform irrigation management. Booker *et al.* (2006) analyzed yields and water use efficiency for spatially varied irrigation over four years for cotton. They concluded that cotton seems to be unpredictable to manage with spatially varied irrigation. This result is supported by the work of Bronson *et al.* (2006).

1.3 Components of precision irrigation system

a. Data acquisition

A Precision Irrigation system requires ability to identify and quantify the variability i.e. spatial and temporal variability that exist in soil and crop conditions within a field and between fields. Existing technology is available to measure the various components of the soil-crop-atmosphere continuum many in real-time so as to provide precise and/or real-time control of irrigation applications.

b. Interpretation

Data has to be collected, interpreted and analyzed at an appropriate scale and frequency. The inadequate development of decision support systems has been identified as a major bottle neck for the interpretation of real time data and adoption of precision agriculture (McBratney *et al.*, 2005).

c. Control

The ability to optimize the inputs and adjust irrigation management at appropriate temporal and spatial scales is an essential component of a precision irrigation system. Applying differential depths of water over a field will be dependent on the irrigation system. Automatic controllers with real time data should provide the most reliable and accurate means of controlling irrigation applications.

1.4 Technology associated with precision irrigation

The advent of precision irrigation methods has played a major role in reducing the quantity of water required in agricultural and horticultural crops, but there is a need for new methods of automated and accurate irrigation scheduling and control. The early adopters found precision agriculture to be unprofitable and the instances in which it was implemented were few and far between. Further, the high initial investment in the form of electronic equipment for sensing and communication meant that only large farms could afford it. The technologies used are *Remote Sensing* (RS), *Global Positioning System* (GPS) and *Geographical Information System* (GIS) and *Wireless Sensor Network* (WSN).

The technology of GIS and GPS apart from being non-real-time, involved the use of expensive technologies like satellite sensing and also labor intensive. Over the last several years, the advancement in sensing and communication technologies has significantly brought down the cost of deployment and running of a feasible precision agriculture framework. However, a stand-alone sensor, due to its limited range, can only monitor a small portion of its environment but the use of several sensors working in a network seems particularly appropriate for precision agriculture. The technological development in Wireless Sensor Networks made it possible to monitor and control various parameters in agriculture. Also recent advances in sensor and wireless radio frequency (RF) technologies and their convergence with the Internet offer vast opportunities for application of sensor systems for agriculture. Emerging wireless technologies with low power needs and low data rate capabilities have been developed which perfectly suit precision agriculture (Wang et al., 2006). The sensing and communication can now be done on a real-time basis leading to better response times. The wireless sensors are cheap enough for wide spread deployment and offer robust communication through redundant propagation paths (Akyildiz & Xudong, 2005). The wireless sensor networks (WSNs) have become the most suitable technology to monitor the agricultural environment.

1.4.1 Wireless Sensor Network (WSN)

Wireless sensor networks (WSN) is a network of small sensing devices known as sensor nodes or motes, arranged in a distributed manner, which collaborate with each other to gather, process and communicate over wireless channel about some physical phenomena. The sensor motes are typically low-cost, low-power, small devices equipped with limited sensing, data processing and wireless communication capabilities with power supply, which perfectly suites the PA/PI (Wang, 1998; Stafford, 2000). A wireless sensor is a self-powered computing unit usually containing a processing unit, a trans-receiver and both analog and digital interfaces, to which a variety of sensing units such as temperature, humidity etc. can be adapted (Fig 1.1). The sensor nodes communicate with each other in order to exchange and process the information collected by their sensing units. If nodes communicate only directly with each other or with a base station, the network is single-hop. In some cases, nodes can use other wireless sensors as relays, in which case the network is said to be multi-hop. In a data-collection model, sensors communicate with one or several base stations connected to a database and an application server that stores the data and performs extra data-processing. The result is available typically via a web-based interface.

1.4.1.1 Wired vs. Wireless Network

Wireless sensor network have a big potential for representing the inherent soil variability present in fields with more accuracy than the current systems available. WSN can operate in a wide range of environments and provide advantages in cost, size, power, flexibility and distributed intelligence, compared to wired ones. The wireless sensors are cheap enough for wide spread deployment in the form of a mesh network and also it offers robust communication through redundant propagation paths (Roy et al., 2008).

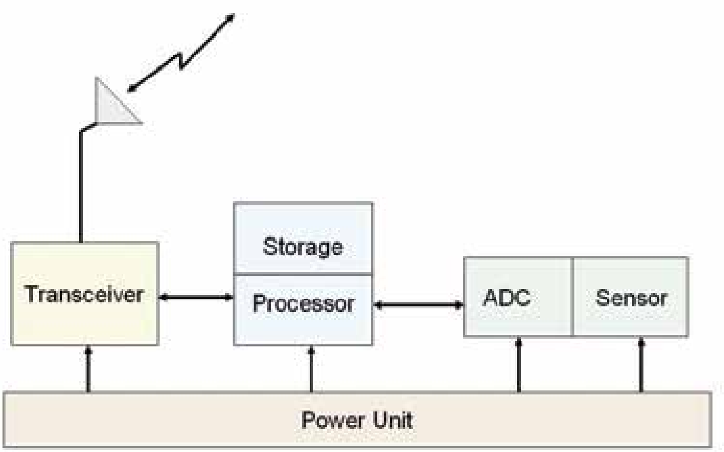


Fig. 1.1. Depiction of Sensor Node

The advantage for wireless sensor network over wired one is the feasibility of installation in places where cabling is impossible. Another obvious advantage of wireless transmission over wired one is the significant reduction in cost and simplification in wiring and harness (Akyildiz et al., 2002). It has been reported that adopting wireless technology would eliminate 20–80% of the typical wiring cost in industrial installations (Wang et al., 2006). However, wired networks are very reliable and stable communication systems for instruments and control. Since installation of WSN is easier than wired network, sensors can be more densely deployed to provide local detailed data necessary for precision agriculture.

Another advantage is their mobility i.e. sensors can be placed on rotating equipment, such as a shaft to measure critical agricultural and environmental parameters. Whenever physical conditions change rapidly over space and time, WSNs allow for real-time processing at a minimal cost. Their capacity to organize spontaneously in a network makes them easy to deploy, expand and maintain, as well as resilient to the failure of individual measurement points. Over the last few years, the advancement in sensing and communication technologies has significantly brought down the cost of deployment and running of a feasible precision agriculture using WSN (Wang, 1998).

Wireless sensor network (WSN), a potential technology found to be suitable for collecting real time data for different parameters pertaining to weather, crop and soil helps in developing solutions for majority of the agricultural processes related to irrigation and other agricultural processes. The development of wireless sensor applications in agriculture makes it possible to increase efficiency, productivity and profitability of farming operations.

2. Irrigation scheduling through evapo-transpiration

Irrigation scheduling defined by Jensen (1981) is as "a planning and decision-making activity" that the farm manager is involved in before and during most of the growing season for each crop that is grown." In other words it is a process through which water lost by the plant through the evapo-transpiration (ET) method is an excellent way to determine how much water to apply based on estimates of the amount of water lost from the crop. Water use efficiency can be achieved with the precisely scheduled irrigation plan. Such a plan on daily basis provides a means of irrigating with an exact amount of water at the targeted dry area to fulfill the needs of evapo-transpiration (ET).

2.1 Evapo-transpiration / crop water requirement (ET)

The combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration is referred to as evapo-transpiration (ET). Evapo-transpiration is also known as water requirement of the crops. The water requirement can be supplied by stored soil water, precipitation, and irrigation. Irrigation is required when ET (crop water demand) exceeds the supply of water from soil water and precipitation. As ET varies with plant development stage and weather conditions, both the amount and timing of irrigation are important. The rate of ET is a function of four critical factors i.e. weather parameters, soil moisture, plant type and stage of development (Allen *et al.*, 1998). Different crops have different water-use requirements under the same weather conditions. The evapo-transpiration rate from a reference surface is called the reference crop ET and denoted as ET_o. The reference sureface is hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec m^{-1} and an albedo (reflectance of the crop-soil surface i.e. fraction of ground covered by vegetation) of 0.23, closely resembling the evapo-transpiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground" (Allen et al., 1989). The grass is specifically defined as the reference crop. The crop coefficients appropriate to the specific crops are used along with the values of reference ET for computing the actual ET at different growth stages of the crop. The modified Penman and Moneith model (shown in equation 2.1) was used to calculate the reference evapotranspiration. The calculation procedures of ET_o by means of the FAO Penman-Monteith equation (Eq. 2.1) are presented by Allen et al (1998).

$$ET_0 = \frac{0.408\ \Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 U_2)} \tag{2.1}$$

Where:
ET_o Reference evapo-transpiration [mm day^{-1}],
R_n Net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m^{-2} day^{-1}],
T Air temperature at 2 m height [°C],
U_2 Wind speed at 2 m height [m s^{-1}],
e_s Saturation vapour pressure [kPa],
e_a Actual vapour pressure [kPa],
e_s - e_a Saturation vapour pressure deficit [kPa],
Δ Slope of vapour pressure curve [kPa °C^{-1}],
γ Psychrometric constant [kPa °C^{-1}].

2.1.1 Actual crop Evapo-transpiration (ET_c)

The crop evapo-transpiration differs distinctly from the reference evapo-transpiration (ET_o) as the ground cover, canopy properties and aerodynamic resistance of the crop are different from grass. The Kc component of equation integrates the characteristics of the crop (e.g., crop height, fraction of net radiation absorbed at the land surface, canopy resistance, and evaporation from bare soil surface) into the ETc estimation equation, to account for the difference in transpiration between the actual crop and the reference grass. The effects of characteristics that distinguish field crops from grass are integrated into the crop coefficient (K_c). In the crop coefficient approach, crop evapo-transpiration is calculated by multiplying ET_o by K_c.

$$ET_c = K_c \times ET_o. \tag{2.2}$$

Where:
ET_c Crop evapo-transpiration [mm day^{-1}],
K_c Crop coefficient [dimensionless],
ET_o Reference crop evapo-transpiration [mm day^{-1}].

2.2 A case study on using Wireless Sensor Network (WSN) in estimating crop water requirement at Sula vineyard, Nashik, India

Grapes cultivation in India is limited due to high recurring cost of cultivation. There is significant variability in the quality of grapes over the years and also within the field. Assessing the yield and quality (both temporal and spatial) is a big challenge for wineries (Das et. al., 2010). Vine soil-water status constitutes one of the main driving factors which affect plant vegetative growth, yield and wine test and quality. Irrigation requirements are currently estimated from winter/summer season as well as berry forming stages. Providing the methods and tools for continuous measurement of soil and crop parameters to characterize the variability of soil water status will be of great help to the grape growers. A wireless sensor network can facilitate creation of a real-time networked database. The real time information from the fields such as soil water content, temperature, and plant characteristics provided a good base for making decisions on irrigation i.e. (when and how much water to apply). The objective of our study was to relate irrigation requirement through evapo-transpiration. The section below describes the agricultural experiments conducted in the grape field which concentrated on monitoring different parameters relating to crop, soil and climate by deploying the wireless sensors network so as to establish a correlation between sensors output and agricultural requirement in terms of water management.

2.2.1 Experimental setup at Green House, IIT Bombay and vineyard at Nashik

Initial deployment of sensors with a wireless sensor network (WSN) in a greenhouse at IIT Bombay (6 X 9 m) provided a pilot scale crop monitoring environment. It was used for testing the ruggedness of WSN for crops grown under controlled conditions in a greenhouse, using sensors embedded in soil and surrounding which was later extended to a larger scale in an intensely cultivated commercial grape farm i.e. Sula vineyard at Nashik (India). Initially the WSN was tested in a greenhouse of 6 X 9 m in the laboratory at Indian Institute of Technology-Bombay (India). Okra plants were planted in nine plots (1.5 X 3 m), with four plants in a row, maintaining a distance between rows and plant of 50 and 30 cms respectively. WSN system deployed consisted of the battery-powered nodes equipped with sensors for continuously monitoring agricultural parameters consisting of air temperature, air relative humidity, soil temperature and soil water content. These parameters were periodically monitored and transmitted in a multi-hop to a centralized processing unit (see section 2.2.2). The measured and recorded values of parameters in real time over a period of 3 months permitted the calculation of evapotranspiration (ET) (Shah et al., 2009). Figure 2.1 shows the schematics of agricultural environment sensors deployed in the field while Fig 2.2 shows the sensors deployed in greenhouse, IIT Bombay.

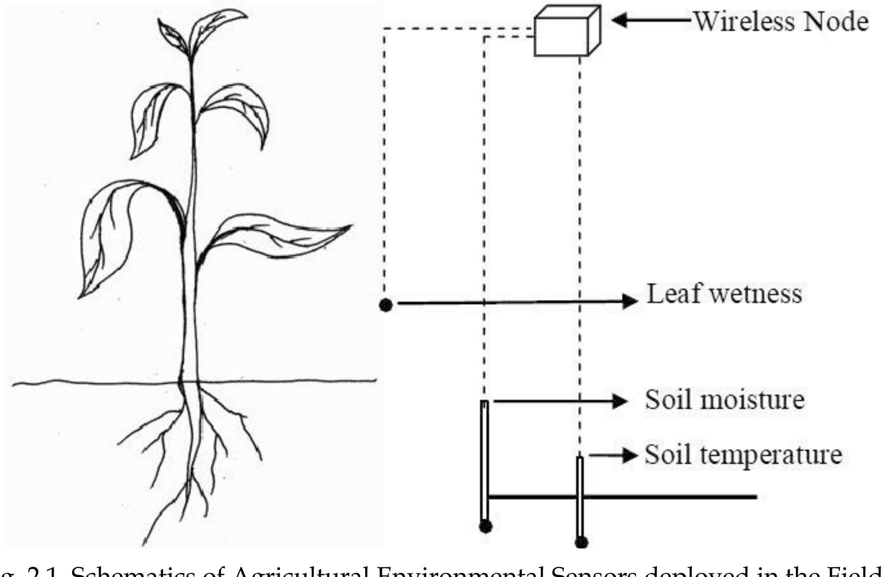


Fig. 2.1. Schematics of Agricultural Environmental Sensors deployed in the Field

Fig. 2.2. Deployment of Wireless sensor network (WSN) System

The WSN system tested at IIT- Lab facility was extended to Sula Vineyard, Nashik (India), for grape crop monitoring as shown in Figure 2.3. The sensors were deployed at a grid of 30 m by 30 m**.** Each node was able to transmit/receive packets to other nodes inside a well-defined transmission range of 30m. WSN system was focused on establishing feasibility of capturing and analyzing data and facilitated global data accessibility from a small number of wireless sensor pods.

Fig. 2.3. Wireless Sensor Network Deployment at Vineyard, Nashik, MH, India

2.2.2 Details of developed Wireless Sensor Network at IIT Bombay

The system designed, developed and deployed at IIT Bombay for its utility for in-field monitoring of grape crop performance, is being popularly known as AgriSens. (Das et. al., 2010). It used a combination of wired and wireless sensors to collect sensory data such as soil pH, soil moisture, soil temperature, etc. Data collected by the sensors were wirelessly transferred in multi-hop manner to a base station node (about 700 m away from the mote) connected with embedded gateway for data logging and correlation. An embedded gateway base station performed elementary data aggregation and filtering algorithms and transmitted the sensory data to Agri-information server via GPRS, a long distance, high data-rate connectivity as illustrated in Fig 2.4. Here the data was processed and stored in a structured database to provide useful information to the farmers to take action such as, e.g., starting or stopping of the irrigation system. The server was situated at Signal Processing Artificial Neural Network lab, Department of Electrical Engineering IIT Bombay, India which is about 200 km away from the fields. The server also supported a real time updated web-interface giving details about the measured agri-parameters (Neelamegam et al., 2007). The closed loop self organizing WSN system used in the study comprised of the following:

- The battery powered nodes with embedded sensors for registering the air temperature and relative humidity were deployed at grid of 30 X 30 m.
- SHT1x is a single chip relative humidity and temperature sensor. The device includes a capacitive polymer sensing element for measuring relative humidity and temperature.
- Networked sensors that measure, and record into an electronics data base, several variables of interest such as soil moisture, soil temperature, pH, ambient relative humidity and ambient temperature. Such automated monitoring system also facilitates the crop experts with a large amount of raw data in electronic formats.
- Each node is able to transmit/receive packets to other nodes inside a well-defined transmission range varying between 30 to 1000 m. A single node can transmit the temperature and relative humidity every minute.
- In a wireless sensor network when the transmission range of a sensor node is not sufficient then it uses multi hop communication to reach the destination node or sink node. For example a node communicates data collected, to a nearby node which in turn transmits to another nearby node in the direction of the sink node. This data forwarding mechanism continues till the sink node is reached. Multi hop communication extends the transmission range of a sensor node and also prevents it from draining soon.
- Signal processing and data processing algorithms that extract useful information out of massive amounts of raw data which is then used to generate alerts that are used to alter sampling frequencies and activate actuators.
- Secure web portal that allows users at different location to access and share their agri-data.
- Solar cell Polycrystalline solar modules (6 V and 500 mA) were used for charging lead acid battery.

2.2.2.1 AgriSens irrigation system

In India, sprinkler and drip irrigation systems are becoming popular irrigation systems. Drip irrigation saves considerable amount of water and hence preferred. As grapevines are arranged in uniform row pattern, drip irrigation is an easy way to control water. Automation can fulfill water requirements of fairly large number of grapevines with single valve. The same pipeline can be used for providing required nutrients also. Grapes are seasonal in India, and they are being planted in month of December to March, which is not a rainy season. Thus, alternate water source has to be used making external source of water essential for grapevines

(Shah et. al., 2009). In vineyard there are different types of grapevines which requires different amount of soil moisture (Burrell et al., 2004). Also, it is very difficult to manually control the irrigation required for particular type of grapevine. WSN based irrigation automation can tackle the problem and also help to save considerable amount of water. The moisture contents of the soil decide the actuator activation. If the threshold level of the soil moisture goes down below a certain level, the valve gets open. This threshold level has to be decided based on climate, topography and type of plant, etc, at the Agri-Information server (Desai et al., 2008). The WSN System, was designed to aid end users and researchers to analyze real time sensor data and assist in decision making for various applications. It was a web based application that could be accessed ubiquitously by the users thus providing a convenient and nimble tool. Since it was integrated with google map, it could provide location-based data. Moreover, this enabled the information to be displayed in a visually readable format.

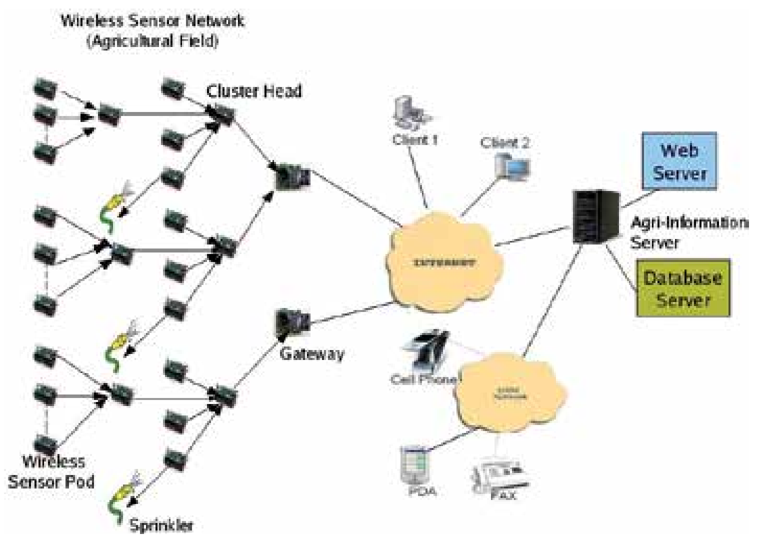


Fig. 2.4. Different Components of Systems Developed at IIT Bombay

2.2.2.2 Sensors suite

Following sensors were deployed based on the feedback received from Sula Vineyard (http://www.sulawines.com) in addition to air temperature and air humidity sensor.

a. Soil moisture sensor

Measuring and monitoring soil moisture helps determining when to irrigate, how much water to apply. The sensor used is ECH2O probe by Decagon as shown in Fig. 2.5 (a). It is a capacitance probe that measures dielectric permeability of medium. In soil, dielectric permeability is related to soil moisture content. Soil moisture was calibrated in terms of volumetric soil moisture content.

b. Soil temperature sensor

The soil temperature shown in Fig 2.5 (b) from Decagon, has a resolution of 0.1◦C. It is enclosed in a low thermal conductivity plastic assembly design to shield the sensor from sunlight and at the same time maximizes convective air movement around the thermistor.

a)

b)

Fig. 2.5. a) Soil Moisture Sensor, b) Soil Temperature Sensor

3. Lessons from the case-study on AgriSens project

3.1 Estimation of Evapo-transpiration (ET) rates for crop okra and grapes

ET is the loss of water from the crop through combined process of soil evaporation and crop transpiration as explained in section 2.1. As discussed earlier, the rate of ET is a function of three critical factors i.e. weather parameters, soil moisture, and nature and stage of growth of the crop. Estimation of ET, to establish the irrigation scheduling using mathematical approach has long been seen as an appealing technique due to simplicity of method when compared with on-site measurements (Allen et al., 1998). ET was estimated using the modified Penman and Moneith model (shown in equation 2.1) to calculate the reference ET and then multiplied with crop coefficient (available in literature) to get the actual crop ET at different growth stages of the crop. The ET for okra was found to vary between 0.1 to 4.0 mm/day, with highest water demand of about 4.0 mm/day during the month of October - December 2007 as shown in Fig 2.7. This is explained by dry climate experienced in Mumbai during month of October to December.

The calculated values of ET for sula vineyard, Nashik were plotted against measured values of soil moisture in Fig. 3.1. Figure 3.1 indicates that soil moisture is influencing the ET loss. This is in agreement with the effect explained by Hatfield and Prueger (2008) and Brown (2000). The rates of ET decreased substantially with decrease in soil moisture content measured over about the top 30 cm depth. Knowing the ideal soil moisture content for crops and given soil texture we can compute the ET and hence irrigation requirement. The

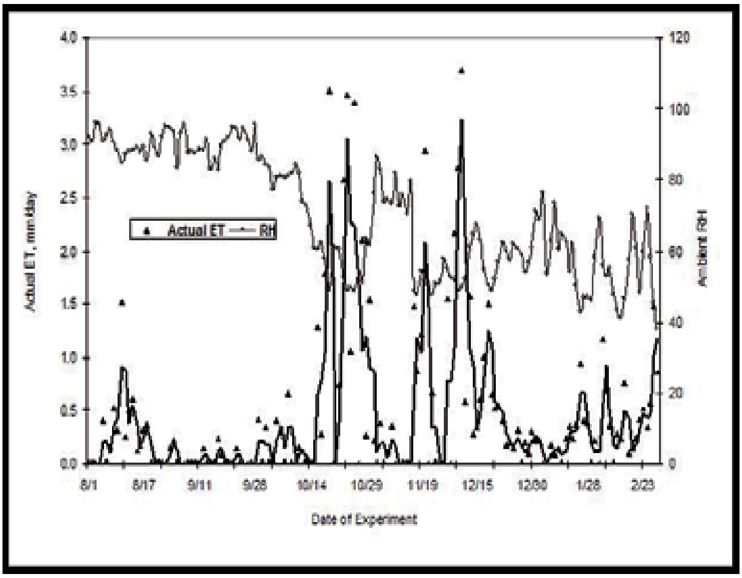


Fig. 3.1. Variation of Evapo-transpiration (ET in mm/day) and Ambient Relative Humidity (RH %) in the Greenhouse, IIT Bombay

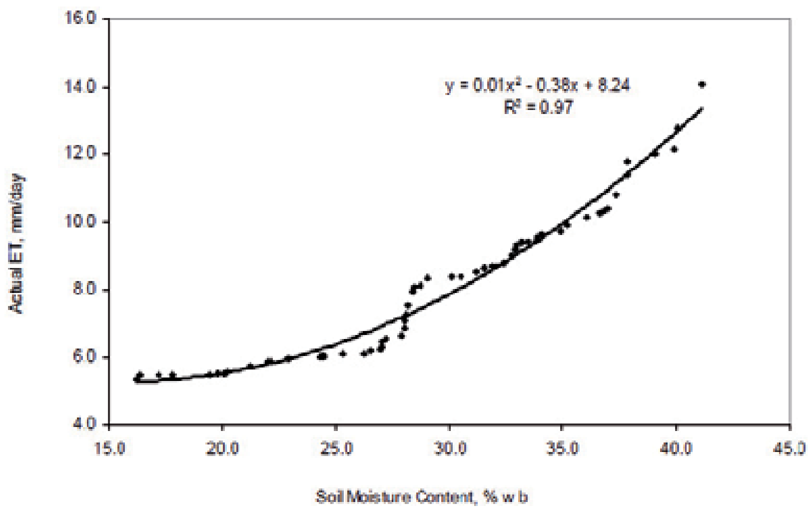


Fig. 3.2. Variation of ET as a Function of Soil Moisture Content, Sula Vineyard, Nashik for the Months of March to May 2008

water requirement through a cycle of 110 days of grape cultivation in the field ranges between 500 to 1200 mm (www.ikisan.com) and the values computed through the sensed parameters in this work ranged from 550-1500 mm. The values of ET for grapes were found to be varying between 5 to 14 mm/day for the months of March till May, 2008. The ET values in grape fields are found to be three times higher than those found in the test bed for okra at IIT Bombay. The field ET for grape crop was computed for the summer months i.e. March to May. The higher ET values for grapevine is further explained by both higher wind velocities in open field and the higher crop coefficients for grapes (0.75) which is almost 1.7 times higher than for okra crop (0.45). The variation in ET values between 5 to 14 mm/day is primarily due to change in soil moisture as the variation in weather data was small.

4. Conclusions

In the past 50 years, world agriculture has experienced enormous changes. Industrialized countries have created a modernized agricultural system with high productivity and advanced technology. Post green-revolution era agriculture in India is facing a technological fatigue for two reasons; a) high rates of ground-water depletion and b) Soil salinity due to excessive irrigation in some pockets. Rapid socio-economic changes in some developing countries are creating new opportunities for application of precision agriculture (PA).

The field deployment case study discussed in the chapter has demonstrated the utility in estimation/saving water use. Weather data monitoring in the shednet house test bed facility at IIT Bombay helped find the ET values for okra ranging between 0.1 to 4 mm/day. The actual ET for grapes in Nashik vineyard, India was found to be varying between 5 to 14 mm/day as the soil moisture varied between 15 to 40 %. While the ET computations were carried out based on data from one season, data for 3- 4 seasons is required for any package of recommended practices as guidelines for entrepreneurs. We believe that WSN supported agriculture management will be particularly useful for larger farms because of its flexibility, more number of sampling points, ease in operation compared to wired sensors- network system. The wide scale appeal of sustainable practices in agriculture and the newer developments in providing low cost/robust sensor based systems are likely to provide the necessary fillip in future agriculture world-wide. Currently the WSN system has high probability of economic viability for high value crops. Despite the widespread promotion and adoption of precision agriculture, the concept of precision irrigation or irrigation as a component of precision agricultural systems is still in its infancy. Some more case studies similar to the one described for other crop-agriculture systems will go a long way in building faith in sensor based irrigation towards both saving precious water as well as soil-degradation due to excessive surface flood irrigation. It also remains to be seen through the field trials that precision irrigation can provide substantially greater benefits than traditional irrigation scheduling. The advances in wireless sensor networks have made some practical deployment possible for various agricultural operations on demonstration scale, which until a few years ago was considered extremely costly or labor intensive. Precision irrigation system with robust components such as, sensing agricultural parameters, identification of sensing location and data gathering, transferring data from crop field to control station for decision making and actuation and control decision based on sensed data will find application in future agriculture. Thus the great potential of integrating the precision farming with WSN to interpolate over a large area for spatial decision making need to be tapped for making agriculture attractive in future.

5. Acknowledgement

The case-study presented here was a part of research project at IIT-Bombay that was supported through a financial contribution from the Department of Information Technology of Ministry of Communications and Information Technology of Government of India. Authors are also grateful for the technical contributions particularly on communication networks (WSN) received from Prof U B Desai and Prof S. N. Merchant of Electrical Engineering Department, IIT-Bombay.

6. References

Adams, M.L.; Cook, S. & Corner, R. (2000). Managing Uncertainty in Site-Specific Management: What is the Best Model? *Precision Agriculture.* 2, 39-54.

Akyildiz, I.F.; Su, W.; Sankarasubramaniam, Y. & Cayirci, E. (2002). Wireless Sensor Networks: A Survey, *Computer Network*, 38, 393-422.

Akyildiz, I.F. & Xudong, W. (2005). A Survey on Wireless Mesh Networks, *IEEE Communication Magazine*, Vol. 43, pp. S23-S30.

Allen, R.G.; Jensen, M.E.; Wright, J.L. & Burman, R.D. (1989). Operational Estimates of Reference Evapo-transpiration, *Agronomy Journal*, 81, pp 650–662.

Allen, R.G.; Pereira, L.S.; Raes, D. & Smith, M. (1998). Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements- FAO Irrigation and Drainage Paper 56. 09-01-2010, Available from http://www.fao.org/docrep/x0490e/x0490e0b.htm.

Booker, J.D.; Bordovsky, J.; Lascano, R.J. & Segarra, E. (2006). Variable Rate Irrigation on Cotton Lint Yield and Fiber Quality. *Belt wide Cotton Conferences*, San Antonio, Texas.

Bronson, K.F.; Booker, J.D.; Bordovsky, J.P.; Keeling, J.W.; Wheeler, T.A.; Boman, R.K.; Parajulee, M.N;, Segarra, E. & Nichols, R.L. (2006) Site-specific Irrigation and Nitrogen Management for Cotton Production in the Southern High Plains. *Agronomy Journal*, 98, 212-219.

Brown, P. (2000). Turf Irrigation Management Series: I, University of Arizona, Cooperative Extension Publication AZ 1194, 09-10-2009, Available from http://ag.arizona.edu/pubs/water/az1194.pdf.

Burrell,J.; Brooke,T. & Beckwith, R. (2004). Vineyard Computing: Sensor Networks in Agricultural Computing, *IEEE Pervasive Computing*, pp 38-45.

Das, Ipsita; Shah N.G. & Merchant, S.N. (2010). AgriSens*: Wireless Sensor Network in Precision Farming: A Case study*. LAP Lambert Academic Publishing, Germany, ISBN: 978-3-8433-5525-4, Germany.

Desai, U.B.; Merchant, S.N.& Shah N.G. (2008). Design and Development of Wireless Sensor Network for Real Time Remote Monitoring. *Unpublished Project Report* submitted to Ministry of Information Technology, Govt of India.

Dukes, M.D. & Scholberg, J.M. (2004) Automated Subsurface Drip Irrigation Based on Soil Moisture. *ASAE Paper No. 052188.*

Evans, R.G. & Sadler, E. (2008) Methods and Technologies to Improve Efficiency of Water Use. *Water Resources Research*, 44.

Goodwin, I. & O'Connell , M.G. (2008). The Future of Irrigated Production Horticulture – World and Australian Perspective. *Acta Horticulturae*, 792, 449–458.

Hatfield, J.L. & Prueger, J.H. (2008). Encyclopaedia of agricultural, food, and biological engineering. D. R. Heldman (Ed). New York: Marcell Dekkar, pp 278-281.

Hedley, C.B. & Yule, I.J. (2009). Soil Water Status Mapping and Two Variable-Rate Irrigation Scenarios. *Precision Agriculture,* 10, 342-355.

Jensen, M.J. (1981). Summary and Challenges. *In Proceeding of the ASAE's Irrigation Scheduling Conf., Irrigation Scheduling for Water & Energy Conservation*, American Society of Agricultural Engineer, St. Joseph, MI. pp. 225-231.

King, B.A.; Stark, J.C. & Wall, R.W. (2006). Comparison of Site-Specific and Conventional Uniform Irrigation Management for Potatoes. *Applied Engineering in Agriculture*, 22(5), 677-688.

Ladha, J. K.; Fischer, A. K.; Hossain, M.; Hobbs, P. R. & Hardy, B. (2000). Improving the Productivity and Sustainability of Rice-Wheat Systems of the Indo-Gangetic

Plains: IRRI Discussion Paper Series No. 40. Makati City (Philippines): International Rice Research Institute. pp 31.

McBratney, A.B.; Whelan, B.; Ancev, T. & Bouma, J. (2005). Future Directions of Precision Agriculture. *Precision Agriculture*, 6, 7-23.

Modak, C.S. (2009). Unpublished Report from Land and Water Management Institute, Aurangabad, Maharashtra, India.

Mondal, P. & Tewari, V.K. (2007). Present Status of Precision Farming: A Review, *International Journal Agricultural Research.* 2(1), pp 1–10.

Neelamegam, S.; Naveen, C. P. R. G.; Padmawar, M.; Desai, U. B.; Merchant, S.N. & Kulkarni, V. (2007). AgriSens: Wireless Sensor Networks for Agriculture- Sula Vineyard A Case Study, *1st International Workshop on Wireless Sensor Network Deployments*, Santa Fe, New Mexico, U.S.A. June 18 – 20.

Panchard, J.; Rao, S.; Prabhakar, T. V.; Hubaux, J.P. & Jamadagni, H. (2007). Common Sense Net: A Wireless Sensor Network for Resource-Poor Agriculture in the Semi-arid Areas of Developing Countries. *Information Technologies and International Development,* Volume 4, Number 1, 51–67.

Pierce, F.J. & Nowak, P. (1999). Aspects of Precision Agriculture. *Advances in Agronomy*, 67, 1-85.

Roy, S.; Anurag, D. & Bandyopadhyay, S. (2008). Agro-sense: Precision Agriculture using Sensor-Based Wireless Mesh Networks. Innovations in NGN: Future Network and Services, In: *Proceedings of the First ITU-T Kaleidoscope Academic Conference*, Geneva, Italy, pp 383–388.

Sadler, E.J.; Evans, R.G.; Stone, K.C. & Camp, C.R. (2005). Opportunities for Conservation with Precision Irrigation. *Journal of Soil and Water Conservation*, 60(6), 371-379.

Schoengold, K.; Sunding, D.L. & Moreno, G. Agricultural Water Demand and the Gains from Precision Irrigation Technology. 12-08-2011, Online available from http://giannini.ucop.edu/media/are-update/files/articles/v7n5_2.pdf.

Shah, N.G.; Desai U.B.; Das, I.; Merchant, S.N. & Yadav, S.S. (2009). "In-Field Wireless Sensor Network (WSN) For Calculating Evapo-transpiration and Leaf Wetness, *International Agricultural Engineering Journal*, 18(3-4), pp 43- 51.

Smith, R.J.; Raine, S.R.; McCarthy, A.C. & Hancock, N.H. (2009). Managing Spatial and Temporal Variation in Irrigated Agriculture Through Adaptive Control. *Australian Journal of Multi-disciplinary Engineering*, 7(1), 79-90.

Stafford, J.V. (2000). Implementing Precision Agriculture in the 21st century. *Journal of Agricultural Engineering Research*, 76, pp 267-275.

Wang, M. (1998). Development of Precision Agriculture and Engineering Technology Innovation, *Transactions of the CSAE, Chinese Society of Agricultural Engineering*. Beijing, 15(1), pp 231.

Wang, N.; Zhang, N. & Wang, M. (2002). Precision Agriculture, A worldwide Overview, *Computers and Electronics in Agriculture*, 36, pp 113-132.

Wang, N.; Zhang, N. & Wang, M. (2006). Wireless Sensors in Agriculture and Food Industry—Recent Development and Future Perspective, Review: *Computers and Electronics in Agriculture*, 50, 1–14.

Whelan, B.M.; McBratney, A.B. & Boydell, B.C. (1997). The Impact of Precision Agriculture. *Proceedings of the ABARE Outlook Conference*, Moree, UK, July, pp 5-7.

Yule, I.J., Hedley, C.B. and Bradbury, S. (2008). Variable-rate irrigation. 12th Annual Symposium on Precision Agriculture Research & Application in Australasia. Sydney.

12

Using Wireless Sensor Networks for Precision Irrigation Scheduling

John D. Lea-Cox
Professor, Department of Plant Science and Landscape Architecture
University of Maryland, College Park
USA

1. Introduction

Worldwide, irrigation uses about 69% of available freshwater resources (Fry, 2005). In the United States, 82% of freshwater resources are used for irrigation purposes. Major concerns on future planetary freshwater resources are the effects of climate change on changing sea temperature and levels, annual snowpack, drought and flood events, as well as changes in water quality, and general ecosystem vulnerabilities (US Global Change Research Program, 2011). Changes in the extreme climatic events are more likely to occur at the regional level than show in national or global statistics. The unpredictability of climatic events is of key concern to farmers in all countries, since the availability and cost of irrigation water is likely to be compounded by increased regulations and competition. Over the past 50 years, the urban demand for freshwater in the United States has also been increasing (Hutson et al. 2004), while the quality of both surface and groundwater has been decreasing due to pollution from both point and nonpoint sources (Secchi et al. 2007). Nitrogen, phosphorus and many other inorganic and organic pollutants such as pesticides and herbicides are being found at increasing concentrations in groundwater under agricultural areas (Guimerà, 1998). As demands on water and the cost of purification increase, the cost of freshwater resources will increase and the availability will likely decrease for agriculture. Population growth in the 20th century increased by a factor of three while water withdrawals increased by a factor of seven during the same time, with little hope of these rates slowing in the near future (Agarwal et al. 2000).

In view of increased competition for resources and the need for increased agricultural production to ensure national and global food security, it is clear that we need to increase our efficiency of irrigation water use, to adapt to these changing conditions. Not only do we need to increase the overall efficiency of irrigation water use to optimize crop yields, but there is also a need to provide farmers with better information on root zone water availability and daily crop water use, especially at critical times during flowering, fruit set and fruit or seed development. Although crop yield is oftentimes related to water use, most growers don't know the water requirement of the crop they grow at any real level of precision. Since irrigation costs in developed countries are usually a small fraction of total production costs, there are few incentives for growers to optimize their use of irrigation water. Therefore, the amount of water applied is mostly based on the availability, rather than actual crop water needs (Balendock et al., 2009). The development of precision (low volume) irrigation systems has played a major role in reducing the water required to maintain yields for high-value crops, but this has also highlighted the need for new methods for accurate irrigation scheduling and control (Jones, 2008). For high-value horticultural crops, there is also significant interest in using precision irrigation as a tool to increase harvest quality through regulated deficit irrigation, and to reduce nutrient loss and fungal disease pressures. In the near future, farmers will likely have to make decisions on how to optimize water use with crop yield, in order to remain competitive. Achievement of any optimal irrigation capability will depend not only on the use of precision irrigation systems, but also on the tools that can help the farmer monitor and automate irrigation scheduling, applying water precisely to satisfy crop water requirements.

1.1 Scope of the chapter

The intent of this chapter is not to provide the reader with an exhaustive review of the sensor network development literature. A simple online search of the keywords "wireless, sensor, network, irrigation" provides links to over 1500 journal articles just within the engineering and biological fields. However, two recent articles do provide excellent current reviews (Ruiz-Garcia et al., 2009) and practical advice (Barrenetxea et al., 2008) for readers wanting more explicit engineering and technical advice on the development and deployment of wireless sensor networks for irrigation, environmental and other (animal and food safety) applications. It is apparent from these and many other articles that the development of operational wireless sensor networks (WSNs) for large-scale outdoor deployment has many challenges; an excellent discussion of many of the pitfalls is given by Barrenetxea et al., (2008). For many of the reasons they and others have outlined, most research in the field of sensor networks for irrigation scheduling has focused on the technical challenge of gathering reliable data from wide area networks. Barrenetxea et al. (2008) note that there are two primary components for successful WSN deployments: (1) gathering the data and (2) exploiting the data. Generally, the engineering component of any WSN project is tasked with providing hardware that reliably accomplishes the first task. However, understanding the biological and/or environmental domain is vital to maximize the trustworthiness of sensor data. Interdisciplinary projects and partnerships are more likely to have a greater chance of success, since the primary objective of all WSN's is to gather data for a specific use, and all partners are focused on that task. However, if we are going to successfully commercialize and deploy sensor networks on farms, the *end-user* must be involved during all stages of the project: from node deployment, to sensor placement and calibration, through to data analysis and interpretation (Tolle et al, 2005; Lea-Cox et al., 2010a). It is this part of the process that has often received scant attention from researchers and developers; the successful integration of sensor networks and decision support systems (software tools) is probably one of the greatest barriers to successful implementation and adoption of these systems by farmers. For this reason, any tools that are developed should be thoroughly vetted by the end-user for ease-of-use, interpretation and applicability. Perhaps most importantly, we should learn from past mistakes where various water-saving technologies have often not achieved any real economic benefit for the grower, in terms of water savings, improved yield, labor cost or other use. Sometimes technology merely adds another "management layer" that requires additional expertise to interpret and use the information, in order to make a decision. We therefore need to bear these considerations in mind when we develop any irrigation scheduling system that aims to improve upon current irrigation management techniques.

This chapter will firstly summarize the pros and cons of certain sensors and techniques that provide promise for use in WSNs for precision irrigation. It will review WSN deployment and progress, but focus primarily on intensive nursery and greenhouse production, since these environments provide some extreme challenges with spatial and temporal sensor measurement, to accurately predict plant water use. We recognize that there are many aspects of plant physiology that provide both feedback and feedforward mechanisms in regulating plant water use, and these may radically change in a crop, pre- and post-anthesis. This chapter is not focused on these challenges; it will however attempt to illustrate the potential of sensor networks to provide real-time information to both farmers and researchers — often at a level of precision that provides keen insights into these processes. Our research and development team (Lea-Cox et al, 2010b) is actively working on deploying and integrating WSNs on farms, but concurrently developing the advanced hardware and software tools that we need for precision irrigation scheduling in intensive horticultural operations. We will illustrate some of our progress with these WSN's in container-production and greenhouse environments, as well as in field (soil-based) tree farms which have soil water dynamics more akin to field orchard environments. Finally, we will discuss challenges and opportunities that need to be addressed to enable the widespread adoption of WSN's for precision irrigation scheduling.

1.2 Intensive production system irrigation scheduling

The most widespread use of automated irrigation scheduling systems are in intensive horticultural, and especially in greenhouse or protected environments (Jones, 2008). Currently, many greenhouse and nursery growers base their irrigation scheduling decisions on intuition or experience (Bacci et al., 2008; Jones, 2008; Lea-Cox et al., 2009). Oftentimes the most basic decision is —"do I need to irrigate today?" While this question could seem trivial, plant water requirements vary by species, season and microclimate, and depend upon any number of environmental and plant developmental factors that need to be integrated on a day-to-day basis. Add to these factors the number of species grown in a 'typical' nursery or greenhouse operation (oftentimes >250 species; Majsztrik, 2011), the variety of container sizes (i.e. rooting volume, water-holding capacity) and the length of crop cycles (a few weeks to several years), it quickly becomes obvious why precision irrigation scheduling in these types of operations is extremely difficult (Lea-Cox et al., 2001; Ross et al, 2001). If done well, daily irrigation decisions take a lot of time and an irrigation manager often faces complex decisions about scheduling, which requires integrating knowledge from many sources. Although these intuitive methods for irrigation scheduling can give good results with experience, they tend to be very subjective with different operators making very different decisions. Many times, even experienced managers make an incorrect decision, i.e., they irrigate when water is not required by the plant. It is also surprising how many "advanced" irrigation scheduling systems automate irrigation cycles *only* on the basis of time, without any feedback-based sensor systems. Thus, even with advanced time-based systems, the decision to irrigate is again based solely on the operator's judgment and the time taken to evaluate crop water use and integrate other information, e.g. weather conditions during the past few days and immediate future.

There are many sensor technologies that have been used over the years to aid this decision process. Various soil moisture measurement devices are available, e.g. tensiometers, gypsum blocks and meters that directly sense soil moisture; additionally pan evaporation, weather station or satellite forecast data can be incorporated into evapotranspiration (E_T) models. However, the widespread adoption of most of this technology has not occurred in the nursery and greenhouse industries, for good reasons. Many sensing technologies which were originally engineered for soil-based measurements have been applied to soilless substrates. Many have failed, largely because these sensors did not perform well in highly porous substrates, since porosity is an important physical property that is necessary for good root growth in containers (Bunt, 1961). Even when a technology has been adapted successfully to container culture (e.g. low-tension tensiometers), often the technology has been too expensive for wide-scale adoption, difficult to incorporate into WSNs, or there have been precision or maintenance issues. Cost and ease of use are key aspects to the adoption and use of any tool by growers, who are often time-limited.

1.3 Wireless sensor network development objectives

It was imperative to establish a list of global objectives for the development of WSN tools and strategies for our project (Lea-Cox et al, 2010b). Jones (2008) documented the features of an 'ideal' irrigation scheduling system for intensive horticultural production systems. He noted that any system should be (1) sensitive to small changes, whether in terms of soil moisture content, evaporative demand, or plant response; (2) respond rapidly to these changes, allowing for continual monitoring and maintenance of optimal water status and responding in "real time" to changing weather conditions; (3) readily adaptable to different crops, growth stages or different horticultural environments without the need for extensive recalibration; (4) robust and reliable; (5) user-friendly, requiring little user training; (6) capable of automation, thus reducing labor requirements, and (7) low cost, both in terms of purchase and running costs.

In addition to these universal requirements, Lea-Cox et al. (2008) proposed a number of more specific WSN requirements, where (1) users should be able to rapidly deploy sensors in any production area, to maximize utility and minimize cost; (2) sensor networks should be scalable, thereby allowing an operation to begin with a small, low-cost system and expand/improve the network over time; (3) nodes (motes) should have low power (battery) requirements, preferably with rechargeable power options; (4) sensor data should be reliably transmitted using wireless connections to the base station computer (or internet) with little or no interference over at least 1000m; (5) the software interface should automatically log and display real-time data from the sensor nodes, in a form that provides the user with an easily interpreted summary of that data, preferably as a customizable graphical output (6) any software control functions should include relatively sophisticated decision tools and discretionary options, to allow for maximum flexibility in scheduling / actuating irrigation solenoids or other control devices.

These engineering objectives are the foundation for our specific scientific, engineering and socio-economic objectives (Lea-Cox, 2010b), to: (1) further develop and adapt commercially-available wireless sensor network hardware and software, to meet the monitoring and control requirements for field (soil-based), container (soilless) production and environmental (green roof) systems; (2) determine the performance and utility of soil moisture and electrical conductivity sensors for precision irrigation and nutrient management; (3) determine spatial and temporal variability of sensors, to minimize the numbers of sensors required for different environments at various scales; (4) integrate various environmental sensors into WSNs to enable real-time modeling of microclimatic plant E_T; (5) integrate soil and environmental data into species-specific models to better predict plant and system water use; (6) develop best management practices for the use of sensors, working with commercial growers to capture needs-based issues during on-farm system development; (7) quantify improvements in water and nutrient management and runoff, plant quality, and yield; (8) evaluate the private and public economic and environmental impacts of precision sensor-controlled practices; (9) identify barriers to adoption and implementation of these practices; and (10) engage growers and the industry on the operation, benefits and current limitations of this sensor / modeling approach to irrigation scheduling and management.

2. Irrigation sensing approaches

The main approaches to irrigation scheduling in soils and the techniques available have been the subject of many reviews over the years. Specific reviews have concentrated on measuring soil moisture (e.g. Dane & Topp, 2002; Bitelli, 2011), physiological measurements (e.g. Jones, 2004; Cifre et al., 2005) or water balance calculations (e.g. Allen et al., 1998). The conventional sensor-based approach has typically scheduled irrigation events on the basis of soil moisture status, whether using direct soil moisture measurements with capacitance or TDR-type sensors (Topp, 1985; Smith & Mullins, 2001), tensiometers (Smajstrla & Harrison, 1998) or soil-moisture water balance methods using daily E_T estimates (Allen et al., 1998). Some automated greenhouse systems have used load cells for the estimation of daily plant water use (Raviv et al., 2000). However, these load cell systems have to be programmed to accurately correct for increasing total plant mass over the crop cycle, or to adjust to changes in wind and temperature changes, if deployed in outdoor environments. Nevertheless, if operated correctly, most of these systems enable much greater precision and improved water use efficiency over traditional time-based irrigation scheduling methods.

Jones (2004) summarized the main sensor techniques that are currently used for irrigation scheduling or which have the potential for development in the near future in some detail (Table 1). The current debate centers around using soil moisture sensing techniques, plant water sensing techniques or a combination of both techniques. Soil irrigation sensing approaches (Table 1) can either be based on direct measurement of soil moisture content (or water potential), or by using sensors to provide data for the water balance method, which accounts for inputs (rainfall, irrigation) and losses (E_T, run-off and drainage) from the system. The emphasis on using soil moisture content for irrigation decisions has been based on the perception that water availability in the soil is what limits plant transpiration, and that irrigation scheduling should replace the water lost by plant water uptake and evaporation from the rootzone (Jones, 2008).

Measurement Technique	Advantages	Disadvantages
I. Soil water measurement (a) Soil water potential (tensiometers, psychrometers, etc.) (b) Soil water content (gravimetric; capacitance / TDR; neutron probe)	Easy to apply in practice; can be quite precise; at least water content measures indicate 'how much' water to apply; many commercial systems available; some sensors (especially capacitance and time domain sensors) readily automated	Soil heterogeneity requires many sensors (often expensive) or extensive monitoring program (e.g. neutron probe); selecting position that is representative of the root-zone is difficult; sensors do not generally measure water status at root surface (which depends on evaporative demand)
II. Soil water balance calculations (Require estimate of evaporation and rainfall)	Easy to apply in principle; indicate 'how much' water to apply	Not as accurate as direct measurement; need accurate local estimates of precipitation /runoff; evapotranspiration estimates require good estimates of crop coefficients (which depend on crop development, rooting depth, etc.); errors are cumulative, so regular recalibration needed
III. Plant 'stress' sensing (Includes both water status measurement and plant response measurement)	Measures the plant stress response directly; integrates environmental effects; potentially very sensitive	In general, does not indicate 'how much' water to apply; calibration required to determine 'control thresholds'; still largely at research/ development stage; little used for routine agronomy (except for thermal sensing in some situations)
(a) Tissue water status	Often been argued that leaf water status is the most appropriate measure for many physiological processes (e.g. photosynthesis), but this argument is generally erroneous (as it ignores root–shoot signaling)	All measures are subject to homeostatic regulation (especially leaf water status), therefore not sensitive (isohydric plants); sensitive to environmental conditions which can lead to short-term fluctuations greater than treatment differences
(i) Visible wilting	Easy to detect	Not precise; yield reduction often occurs before visible symptoms; hard to automate
(ii) Pressure chamber (ψ)	Widely accepted reference technique; most useful if estimating stem water potential (SWP), using either bagged leaves or suckers	Slow and labor intensive (therefore expensive, especially for predawn measurements); unsuitable for automation
(iii) Psychrometer (ψ)	Valuable, thermodynamically based measure of water status; can be automated	Requires sophisticated equipment and high level of technical skill, yet still unreliable in the long term
(v) Pressure probe	Can measure the pressure component of water potential which is the driving force for xylem flow and much cell function (e.g. growth)	Only suitable for experimental or laboratory systems

(vi) Xylem cavitation	Can be sensitive to increasing water stress	Cavitation frequency depends on stress prehistory; cavitation–water status curve shows hysteresis, with most cavitations occurring during drying, so cannot indicate successful rehydration
(b) Physiological responses	Potentially more sensitive than measures of tissue (especially leaf) water status	Often require sophisticated or complex equipment; require calibration to determine 'control thresholds'
(i) Stomatal conductance	Generally a very sensitive response, except in some anisohydric species	Large leaf-to-leaf variation requires much replication for reliable data
– Porometer	Accurate: the benchmark for research studies	Labor intensive so not suitable for commercial application; not readily automated (though some attempts have been made)
– Thermal sensing	Can be used remotely; capable of scaling up to large areas of crop (especially with imaging); imaging effectively averages many leaves; simple thermometers cheap and portable; well suited for monitoring purposes	Canopy temperature is affected by environmental conditions as well as by stomatal aperture, so needs calibration (e.g. using wet and dry reference surfaces

Table 1. A summary of the main classes of irrigation scheduling techniques, indicating the major advantages and disadvantages (from Jones, 2004). Reproduced with kind permission of the author and Oxford University Press.

2.1 Measuring soil moisture

2.1.1 Water potential or volumetric water content?

Soil (substrate) water content can be expressed either in terms of the energy status of the water in the soil (i.e. matric potential, kPa) or as the amount of water in the substrate (most commonly expressed on a volumetric basis; % or $m^3 \cdot m^{-3}$). Both methods have advantages and disadvantages. Soil/substrate matric potential indicates how easily water is available to plants (Lea-Cox et al, 2011), but it does not provide information on how much total water is present in the substrate. Conversely, volumetric water content indicates how much water is present in a substrate, but not if this water is extractable by plant roots. This is especially important for soilless substrates, since mixtures of different components means that substrates have very different water-holding capacities and moisture release curves (deBoodt and Verdonck, 1972). Sensors that estimate water content (e.g. capacitance and TDR-type sensors) tend to be more reliable than those sensors measuring water availability (tensiometers and psychrometers); (Jones, 2008; Murray et al, 2004). A major disadvantage of almost all soil sensors, however, is their limited capability to measure soil moisture heterogeneity in the root zone, since they typically only sense a small volume around the sensor. Variation in soil water availability is well known, primarily as a function of variation in soil type, soil compaction and depth, among many sources of variation (e.g. organic matter content, porosity and rockiness). The use of large sensor arrays which may be necessary to get good representative readings of soil moisture tends to be limited by cost, but this could be overcome by sensor placement strategies.

Soilless substrates are used by the nursery and greenhouse industry for a multitude of reasons, primarily to reduce the incidence of soil-borne pathogens, increase root growth, and reduce labor, shipping and overall costs to the producer (Majsztrik et al., 2011). Over the years, many studies have shown large differences between soil and soilless substrates in the availability of water to root systems (Bunt, 1961; deBoodt and Verdonck, 1972). Soilless substrates, which in most cases have larger particle sizes and porosity, tend to release more water at very low matric potentials (Ψm=-1 to -40 kPa) which is 10 to 100 times lower than similar plant-available water tensions in soils (Lea-Cox et al., 2011). Plant-available water (PAW) is the amount of water accessible to the plant, which is affected by the physical properties of the substrate, the geometry (height and width) of the container and the total volume of the container (Handreck and Black, 2002). Container root systems are usually confined within a short time after transplanting, and shoot : root ratios are usually larger than those of soil-grown plants, for similarly-aged plants. For all these reasons, maintaining the optimal water status of soilless substrates has been recognized as being critical for continued growth, not only because of limited water-holding capacity, but also because of the inadequacies of being able to accurately judge when plants require water (Karlovich & Fonteno, 1986). Although it is likely that mature plant root systems can extract substrate moisture at Ψm less than -40 kPa, Leith and Burger (1989) and Kiehl et al. (1992) found significant growth reductions at substrate Ψm as small as -16 kPa (0.16 Bar). This has major implications for choosing appropriate sensors for use in soilless substrates (see next section), as well as the measurement and automatic control of irrigation in these substrates.

2.1.2 Types of soil moisture sensors

Jones (2004) noted the various types of soil moisture sensors available at that time. The variety of soil moisture sensors (tensiometric, neutron, resistance, heat dissipation, psychrometric or dielectric) has continually evolved since then; the choices are now overwhelming, since each sensor may have specific strengths and weaknesses in a specific situation. Tensiometers have long been used to measure matric potential in soils (Smajstrla & Harrison, 1998) and in soilless substrates (Burger and Paul, 1987). Although tensiometers have proven to be valuable research tools, they have not been adopted widely in greenhouse and nursery production, mainly because of the problems with using them in highly porous soilless substrates. Tensiometers rely on direct contact between the porous ceramic tip and substrate moisture. If the substrate shrinks, or the tensiometer is disturbed, this contact may be disrupted. Air then enters and breaks the water column in the tensiometer, resulting in incorrect readings and maintenance issues (Zazueta et al., 1994). A number of next-generation soil moisture sensors have become available in the past decade from various manufacturers., e.g. Theta probe and SM200 (Delta T, Burwell, UK) and EC5, 5TM and 10HS sensors (Decagon Devices Inc., Pullman, WA, USA) which provide precise data in a wide range of soilless substrates. These sensors determine the volumetric moisture content by measuring the apparent dielectric constant of the soil or substrate. These sensors are easy to use and provide highly reproducible data (van Iersel et al., 2011). The Decagon range of sensors are designed to be installed in soils or substrates for longer periods of time and all interface with Decagon's range of EM50 nodes, datastation and Datatrac software (http://decagon.com/products). Dielectric sensors generally require substrate-specific calibrations, because the dielectric properties of different soils and substrates differ, affecting sensor output. The conversion between water potential and volumetric water content (VWC) varies substantially with soil type. It is possible to inter-convert matric potential to volumetric water content (Lea-Cox et al, 2011) for various sensors using substrate moisture release curves. However, such release curves are substrate-specific, and may change over time as the physical properties (e.g. pore size distribution) of the substrate changes (van Iersel et al., 2011) or root systems become more established. Fortunately, in most irrigation scheduling applications, the objective is simply to apply a volume of water that returns the soil moisture content to its original well-watered state. Changes in this total water-holding capacity (i.e. the maximum VWC reading) can easily be monitored for changes over time, i.e. after significant rainfall events or by periodically saturating the container with the embedded sensor.

More recently, hybrid 'tensiometer-like' sensors have been developed which use the principle of dielectric sensors to determine the water potential of substrates (e.g., Equitensiometer, Delta T; MPS-1, Decagon Devices) (van Iersel et al., 2011). An advantage of such sensors is that they do not require substrate-specific calibrations, since they measure the water content of the ceramic material, not that of the surrounding soil or substrate. Unfortunately, the sensors that are currently available are not very sensitive in the matric potential range where soilless substrates hold most plant-available water (0 to -10 kPa; deBoodt and Verdonck, 1972). In addition, it is not clear whether these sensors respond quickly enough to capture the rapid changes that can occur in soilless substrates (van Iersel et al., 2011).

2.2 Measuring plant water status

Automated irrigation techniques based on sensing plant water status are mostly in the developmental stage, in large part because of the variability of sensor readings and the lack of rugged sensors and reliable automated techniques (Table 1). It is usually necessary to supplement indicators of plant stress with additional information, such as crop evaporative demand (Jones, 2008); it is also hard to scale up these automated systems for many horticultural applications, since a detailed knowledge of crop development is required. Plant water use (transpiration) is a key process in the hydrologic cycle, and because photosynthetic uptake of CO_2 and transpiration are both controlled by stomata, it is strongly linked to plant productivity (Jones & Tardieu, 1998). Models that can accurately predict transpiration therefore have important applications for irrigation scheduling and crop yield. However, previous evidence (Jones, 2004) suggests that leaf water status is not the most useful indicator of plant water stress, and cannot therefore be used as the primary indicator of irrigation need as has sometimes been suggested. In fact leaf water status depends on a complex interaction of soil water availability and environmental and physiological factors (Jones, 1990). It is now clear that in some situations soil water status is sensed by the roots and this information is signaled to the shoots, perhaps by means of hydraulic signals (Christmann et al., 2009) and chemical messengers such as abscisic acid (Kim & van Iersel, 2011). Another general limitation to plant-based methods is that they do not usually give information on 'how much' irrigation to apply at any time, only whether irrigation is needed or not. None of the plant-based methods illustrated in Table 1 are well-adapted for automatic irrigation scheduling or control because of the difficulties measuring each variable (Jones, 2008). Typically, the use of any plant-based indicator for irrigation scheduling requires the definition of reference or threshold values, beyond which irrigation is necessary. Such threshold values are commonly determined for plants growing under non-limiting soil water supply (Fereres and Goldhamer, 2003), but obtaining extensive information on the behavior of these reference values as environmental conditions change will be an important stage in the development and validation of such methods.

2.3 Hybridizing sensing and modeling techniques for precision irrigation scheduling

Water budget calculations are relatively easy to use in scheduling irrigations, since there are simple algorithms available to calculate crop E_T (typically using Penman-Monteith or other methods) that use local meteorological station or pan evaporation data (Fereres et al., 2003). All methods are based on calculating a reference E_T that is multiplied by an empirically-determined crop coefficient (Kc) for each crop. At present there are good estimates of Kc values for many horticultural crops, even though most research has been conducted on the major field crops (Allen et al, 1998). However, there are virtually no K_C values for ornamental species and most estimates of woody perennial crop water use are quite variable. Inaccuracies in Kc values can result in large potential errors in estimated soil moisture contents (Allen et al., 1998). The approach therefore works best where it is combined with regular soil moisture monitoring techniques that can help reset the model (e.g. after rainfall). A particular strength of book-keeping and volumetric soil-based approaches is that they not only address scheduling issues about "when to irrigate" but also about "how much to apply". Although useful for soil-based irrigation scheduling, there may be limitations on how quickly these calculations can be manually performed. This is especially important for greenhouse and container-nursery operations who may be cyclic irrigating containerized plants from 4-8 times per day (Tyler et al., 1996) to maintain available water in the root zone on hot, sunny or windy days.

Previous studies with a variety of crop, ornamental and turf species have reported that the use of appropriate scheduling methods and precision irrigation technologies can save a significant amount of water, while maintaining or increasing yield and product quality (Bacci et al., 2008; Beeson & Brooks, 2008; Blonquist et al., 2006; Fereres et al., 2003). Many of these empirical approaches have successfully incorporated environmental variables into various models, to further increase the precision of irrigation scheduling (e.g. Treder et al., 1997). It is imperative that we connect our capability for precision water applications with a knowledge of real-time plant water use. We need to improve our ability to predict plant water use in real-time using various technologies. As an example of this approach, van Iersel and his group have shown with various studies (Burnett and van Iersel, 2008; Kim and van Iersel, 2009; Nemali and van Iersel, 2006; van Iersel et al., 2009; 2010; 2011) that automated irrigation using soil moisture sensors allows for the very precise irrigation of greenhouse crops in soilless substrates. In addition, they maintained very low substrate moisture contents at very precise levels which advances our capability to use precision irrigation scheduling for regulated deficit irrigation (RDI) techniques (Jones, 2004), to increase fruit crop quality (Fereres et al., 2003), and aid in precision nutrient (Lea-Cox et al, 2001; Ristvey et al, 2004) and disease management (Lea-Cox et al, 2006).

Most recently, Kim and van Iersel (2011) have demonstrated that the measured daily evapotranspiration of petunia in the greenhouse can be accurately modeled with measurements of crop growth (days after planting, DAP), daily light integral (DLI), vapor pressure deficit (VPD) and air temperature. All these environmental fluxes obviously affect transpiration on a continuous basis. Ambient light affects plant water use due to its effects on evaporation and stomatal opening (Pieruschka et al., 2010). Vapor pressure deficit is the driving force for transpiration and also affects stomatal regulation (Taiz and Zeiger, 2006) while temperature affects E_T and plant metabolic activity (Allen et al., 1998; van Iersel, 2003). The importance of Kim & van Iersel's empirical modeling approach is how they have demonstrated the sensitivity of plant water use to these four easily-measured variables. Thus, with a few inexpensive sensors (temperature, relative humidity and photosynthetic photon flux, PPF) and some simple software tools that can integrate these variables on short time-scales, it now appears possible to predict hourly plant water use for greenhouse crops with real precision. It should be noted however, that these models still require rigorous validation for production conditions.

However, for these types of models to work in an external environment, it is likely that the complexity of our predictive water use models will have to increase, to incorporate additional variables. Water use by perennial woody crop species is much more complicated due to external environmental conditions (for example how VPD and leaf temperature are affected by wind speed and boundary layer effects on canopies; LAI effects on PPF interception). For example, Bowden et al. (2005) outlined an automated sensor-based irrigation system for nurseries that could calculate plant water consumption from species and genotype-specific plant physiological responses. The MAESTRA [Multi-Array Evaporation Stand Tree Radiation A] model (Wang and Jarvis, 1990) is a three-dimensional process-based model that computes transpiration, photosynthesis, and absorbed radiation within individual tree crowns at relatively short time (15-minute) intervals. The model is described more fully by Bauerle & Bowden (2011b) and has been modified and previously validated to estimate deciduous tree transpiration (Bauerle et al., 2002; Bowden & Bauerle, 2008) and within-crown light interception (Bauerle et al., 2004). The model applies physiological equations to sub-volumes of the tree crown and then sums and/or averages the values for entire canopies. Additionally, species-specific physiological values can be incorporated into model calculations, potentially yielding more accurate estimates of whole tree transpiration. The model holds potential advantages for nursery, forest, and orchard water use prediction in that structural parameters such as tree position, crown shape, and tree dimensions are specified.

Bowden et al. (2005) briefly illustrated how the model estimates of water use and plant water requirements are outputted from MAESTRA and used to both make irrigation decisions (command executed by a sensor node) and visualize model updates via a graphic user interface (Bauerle et al., 2006). Within each 15-minute time step, the model adjusts transpiration based on interactions between environmental, soil moisture, and plant physiological response. The substrate moisture deficit calculation is described in Bauerle et al. (2002). An updated substrate moisture value is carried into the next time step for input into the substrate moisture deficit sub-routine. The calculated moisture deficit value is one of the input values required to calculate the amount of stomatal conductance regulation and hence, interacts with other equations to derive whole plant water use. Overall, this GUI (Bowden et al., 2005; Bauerle et al., 2006) provides a user friendly interface to a complex set of calculations. In this way, whole tree water use estimates can be rapidly visualized for either sensor node or human based irrigation decision management. Bauerle and his group are actively working to further refine the MAESTRA model for incorporation into the irrigation scheduling decision support system in our current project (Lea-Cox et al., 2010b).

3. Utilizing the power of sensor networks

3.1 Wireless Sensor Networks

A WSN is typically comprised of radio frequency transceivers, sensors, microcontrollers and power sources (Akyildiz et al., 2002). Recent advances in wireless sensor networking technology have led to the development of low cost, low power, multifunctional sensor nodes. These nodes can be clustered in close proximity to provide dense sensing capabilities, or deployed in a more distributed fashion (Fig. 1). We shall describe the commercially-available Decagon Devices WSN, since we have the most experience with that system, although there are other commercial companies that have similarly available irrigation and environmental WSN systems, e.g. Adcon Telemetry Int. (Klosterneuburg, Austria; http://adcon.at), Delta-T Devices (Cambridge, UK; http://delta-t.co.uk) and PureSense (Fresno, CA; http://puresense.com).

Figure 1 shows the type of WSN that we have deployed in multiple research and commercial sites. Whenever necessary, the accumulated data is transmitted from each of the sensor nodes in the production area using a 900 MHz radio card (although other companies use other frequencies), to a 'base' datastation connected to a personal computer on the farm. Incoming data is inputted into a software program (e.g. DataTrac v.3.2; Decagon Devices) that is installed on a low-cost computer. The software then plots and displays the sensor information from each of the nodes. Data is appended to existing data, so information can be graphically displayed over multiple time scales, depending on user preference. Alternatively, data from a field node can be transmitted directly to a server via the internet using a 3G wireless node (e.g. EM50G, Decagon Devices). The logged data is then accessed from the server over an internet website, using the same DataTrac software previously described. In this way, a grower can develop a scaleable network of sensors that allows for the monitoring of soil moisture and environmental data, in real time. The advantages of these WSN's are fairly obvious – they provide information at the "micro-scale" which can be expanded to any resolution, determined for a specific production operation, for specific needs. This system also provides a mechanism for local (i.e. a decision made locally by the node, based on local sensor readings /setpoints) or the global control (information relayed to the nodes from an external database) of irrigation scheduling (Fig. 1) , depending upon grower preferences and needs (Kohanbash et al, 2011). We are currently in the process of deploying and testing next-generation nodes with these various capabilities.

Any combination of environmental sensors, including soil moisture and electrical conductivity, soil and air temperature, relative humidity, anemometer (wind speed and direction), rain gauge and light (PPF and net radiation) sensors can be connected to the nodes, according to user needs. Decagon nodes collect data every minute, which is averaged and logged on a 1, 5- 15-min or greater time scale, according to required precision. Longer sampling times result in a considerable increase in battery life, but power consumption will also vary greatly with different systems. With Decagon EM50 nodes, a 15-min average setting typically results in > 12-month battery life from 5 'AA' batteries under normal temperature (-5 to 40°C) conditions (J.D. Lea-Cox, *pers. obs.*). Battery life is also affected by the number of times the field nodes are downloaded and the settings employed; typically nodes are downloaded 1-10 times a day.

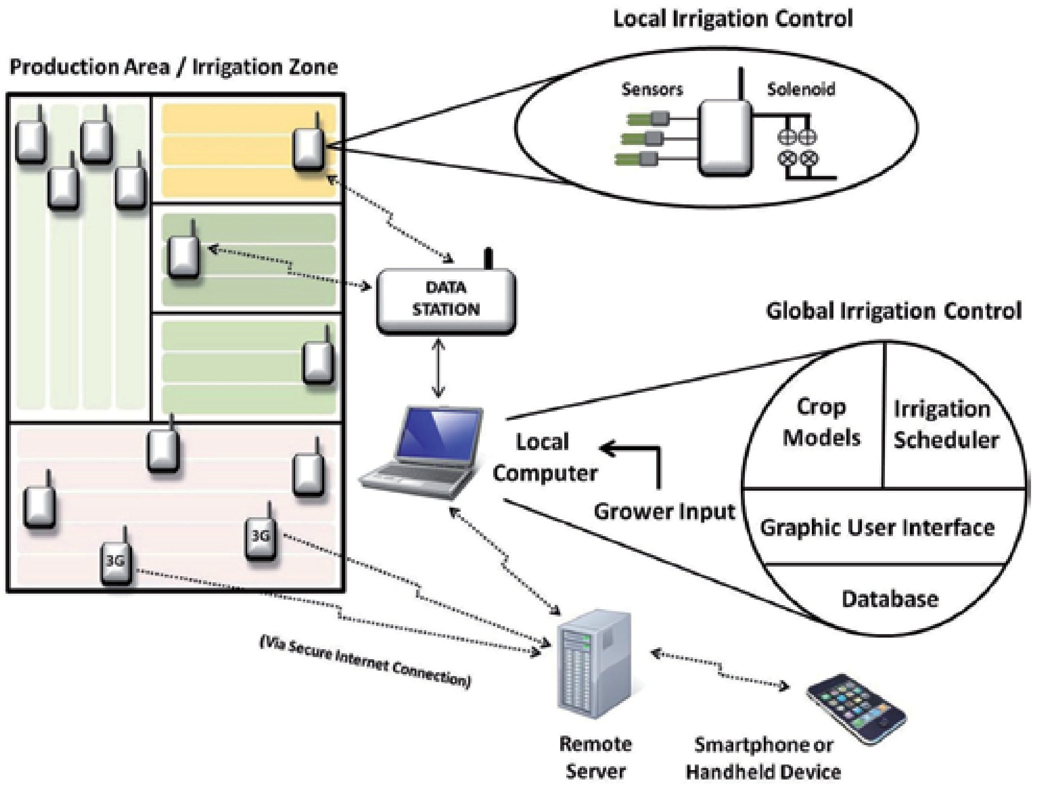


Fig. 1. A schematic of a farm-scale WSN for precision irrigation scheduling (adapted from Balendock, 2009), to illustrate networks deployed by our group (Lea-Cox et al., 2010b).

3.2 Scaleable, adaptable and reconfigurable capabilities

One of the most important features of these WSNs is that a grower can purchase a small network and scale up and/or reconfigure the sensor network to meet specific needs, over time. These networks can provide a fixed capability, but networks can be more fully utilized if a "nimble networks" concept is used. In this way, growers can move sensor nodes quickly and easily within the production area for shorter periods of time, to address current issues and problems, e.g. to address the water requirements of a specific indicator species in a drought, or to monitor irrigations to reduce the incidence of disease in a crop (Lea-Cox et al., 2006). This nimble network approach can more fully utilize WSN capabilities and is one of the most powerful ways of realizing a quick return on investment in equipment. We think that there are many situations where a grower could have a payback period for a small network within a single crop cycle, if the information is utilized for better irrigation and crop management decisions.

3.3 Wireless sensor network development for irrigation scheduling

A number of WSN's with various topologies (e.g. star, mesh-network) have been developed and investigated by different researchers in the past decade (Ruiz-Garcia et al., 2009), including WSN's for irrigation scheduling in cotton (Vellidis et al., 2008), center-pivot irrigation (O'Shaughnessy & Evett, 2008) and linear-move irrigation systems (Kim et al., 2008). The first reported greenhouse WSN was a bluetooth monitoring and control system developed by Liu & Ying (2003). Yoo et al. (2007) describes the deployment of a wireless environmental monitoring and control system in greenhouses; Wang et al. (2008) also developed a specialized wireless sensor node to monitor temperature, relative humidity and light inside greenhouses. Our group (Lea-Cox et al., 2007) reported on the early deployment of a WSN within a cut-flower greenhouse, where a number of soil moisture and environmental sensor nodes were deployed for real-time monitoring of crop production by the grower.

With regards to large on-farm WSN deployments, Balendonck et al., (2009) reported on the FLOW-AID project that has many of the same objectives that we are focused upon, i.e., providing growers with a safe, efficient and cost-effective management system for irrigation scheduling. The FLOW-AID project is integrating innovative monitoring and control technologies within an appropriate decision support system (Balendonck et al., 2007; Ferentinos et al., 2003) that is accessible over the internet, to assist growers in long-term farm zoning and crop planning. It is especially focused on providing growers with regulated deficit irrigation and soil salinity management tools. To support shorter-term irrigation scheduling, a scheduling tool is being developed which allocates available water among several plots and schedules irrigation for each plot (Stanghellini et al., 2007; Anastasiou et al., 2008). To assist this advanced scheduling tool, a crop response model is being developed and used to predict crop stress (Balendonck et al., 2009).

We outlined the major engineering and scientific goals of our WSN project earlier in this chapter (Lea-Cox et al., 2010a). To explain further, this interdisciplinary project is taking a commercially-available WSN product (Decagon Devices, Inc.) and retooling it to support the irrigation scheduling requirements of field nurseries, container nurseries, greenhouse operations and green roof systems, as analogs for many intensive agricultural production and environmental management systems. Our global goals are to develop a more integrative and mechanistic understanding of plant water requirements, to more precisely schedule irrigation events with WSN technology. We are working across various scales of production, using small and large commercial farms which allow us to take a systems approach to defining the hardware and software required to meet the needs of these highly intensive specialty crop systems. In addition to the ornamental industry, there are many parallel needs that we are addressing for WSN adoption by field-grown fruit, nut and berry production, as well as field and greenhouse vegetable production. As part of the project, economic, environmental and social analyses will identify costs and benefits of WSN technology to the industry and society, including barriers to adoption. The project directly involves commercial growers throughout the process, using deployments in commercial operations as test sites. This will help ensure product satisfaction of the next generation of hardware and software developed by our various teams (Lea-Cox et al., 2010b; http://www.smart-farms.net). Each farm and research test site is instrumented with a sensor network(s) to provide real-time environmental data for scientific and technological development. Data streams are monitored on a day-to-day basis by growers, engineers and scientists, which drives a daily dialogue between the growers and various working groups.

The role of the engineering team is to develop, deploy and maintain the next generation of wireless sensor networks (Fig. 1). Their major task is to develop the hardware and software capable of supporting advanced monitoring and control of irrigation scheduling, implementing a hybrid sensor and modeling approach. A major focus of this effort is the development of advanced software which will provide advanced user control, in addition to database filtering and analysis. The software will refine incoming data and provide an easy-to-use computer program for a non-expert user to easily visualize the information from the WSN, and schedule irrigation events based on user preference, or utilizing automatic (set-point) control. The scientific modeling group (Bauerle et al., 2011a; Kim and van Iersel, 2011; Starry et al., 2011) are developing and validating the various models, which form the basis of the species- and environmental-specific software. These models interface with the WSN database via an open application programming interface, which integrates the models with the irrigation scheduling monitoring and control functions. This will enable more predictive (feed-forward) management of water use, based upon the underlying plant and environmental water-use models.

The role of the scientific and extension teams is to ensure that the precision and accuracy of the data gathered (and hence the quality of the models incorporated in the decision support software) are of the highest possible quality and reliability. There are a number of critical research objectives that span the various production environments: (a) characterize the spatial and temporal variability of environmental parameters in both root and shoot canopies, since we need to place sensors for maximum precision and economic benefit; (b) characterize sensor performance and precision, so we match the right sensor with the right application; (c) integrate the knowledge gained from (a) and (b), to ensure that the irrigation scheduling decisions made (either manually or automatically) satisfy plant water requirements in real-time, while placing a minimum burden on the grower for managing the system. We elaborate further on some of these critical objectives below in section 3.4. However, our primary project objective is to provide a cost-effective WSN that provides quality data for minimal cost to growers, both small and large. Our grower's production areas range from 0.5 to over 250 ha in extent, with multiple irrigation zones / crop species. To that end, our economic and environmental analysis team members are gathering specific economic, resource use and environmental data from each production site through a series of on-farm visits and assessments. Larger outreach (survey) efforts across the United States will validate results from our intensive economic analysis of the commercial operations in the study. Some early WSN deployment strategies and results from the project are illustrated later in this chapter. Further project information, results and learning modules are available from our interactive website at http://www.smart-farms.net.

3.4 Sensor network deployment issues and strategies

3.4.1 Spatial and temporal variability

Understanding spatial and temporal variability of environmental data is one of the most important aspects of deploying WSNs in any real-world application, since these dynamics not only determine the appropriate position of a sensor, but the precision of the sensor data is of course greatly affected by the immediate environment and the forces acting on that environment. This is the realm of environmental biophysics (Campbell and Norman, 1998; Jones, 1992) and environmental plant physiology (Nobel, 2009) which forms the basis of our efforts to sense and model the environment.

Figure 2 illustrates soil moisture variability from 10HS soil moisture sensors at two depths (15 and 30cm below the soil surface) in five replicate *Acer rubrum* (Red maple) trees from May through Sept., 2009 (Lea-Cox, unpublished data). Sensors were calibrated to the specific soil type found on this farm (Lea-Cox, Black, Ristvey & Ross, 2008).

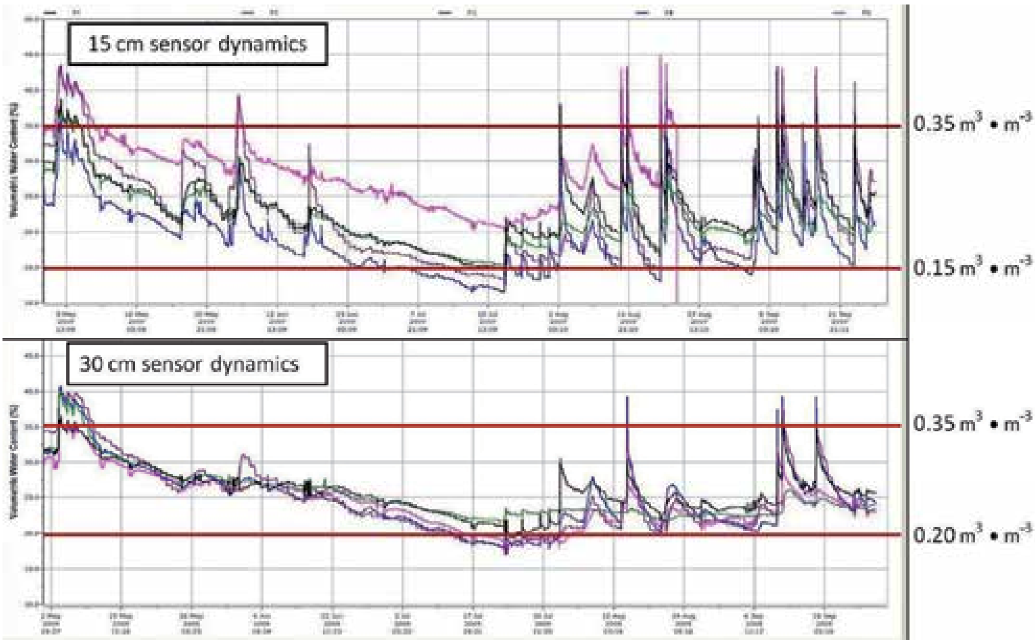


Fig. 2. Soil moisture dynamics at 15cm and 30cm depths in the root zone of five replicate *Acer rubrum* trees from May through September, 2009. Stacked data from two nodes is graphically displayed using an earlier version of DataTrac (v. 2.78, Decagon Devices).

As can be seen, 15cm data were more variable throughout the entire season (Fig. 2). Trees were irrigated for 1-2 hours with drip irrigation on a daily basis throughout most of the study (Lea-Cox, Black, Ristvey & Ross, 2008), except after major rainfall events restored the soil water contents above 0.25 $m^3 \bullet m^{-3}$ (Fig. 2). Changes in daily water content (tree uptake) are evident immediately after these rainfall events, particularly in the 15cm dynamics. Soil moisture dynamics at the 30cm depth were much less variable between trees at all times during the season, and soil moisture at this depth did not fall below 0.20 $m^3 \bullet m^{-3}$ during this year, despite relatively low rainfall totals during the summer (data not shown).

Figure 3 shows similar soil moisture data from 10HS sensors at 15cm depth from *Cornus florida* trees, but these trees were grown in a pine bark soilless substrate in 56-liter containers in a container-nursery operation. Firstly, note that the average substrate moisture is around 0.5 $m^3 \bullet m^{-3}$, since this organic substrate has a high water-holding capacity and also because this grower typically irrigates 2-3 times per day, with small low-volume microsprinkler events (1.5L in 6 minutes) during summer months.

Note also how quickly substrate moisture decreases with plant uptake when morning and early afternoon irrigation events are skipped, due to the relatively low amounts of total water in the container (Fig. 3). Note also that real-time irrigation applications per tree are easily measured using a small tipping rain gauge with a rain cover, with an additional microsprinkler head inserted under the cover (Lea-Cox et al., 2010b). The volumes displayed (Fig. 3) give the grower instantaneous feedback and tie soil moisture contents directly to irrigation events and the volumes applied. We are using the same tipping rain gauges to give leaching volumes from pot-in-pot containers with an underground drainage system, to provide approximate daily irrigation water budgets (i.e. Irrigation + Rainfall - Leaching = $\delta VWC \approx E_T$) for additional indicator species on the farm (Lea-Cox et al., 2010b).

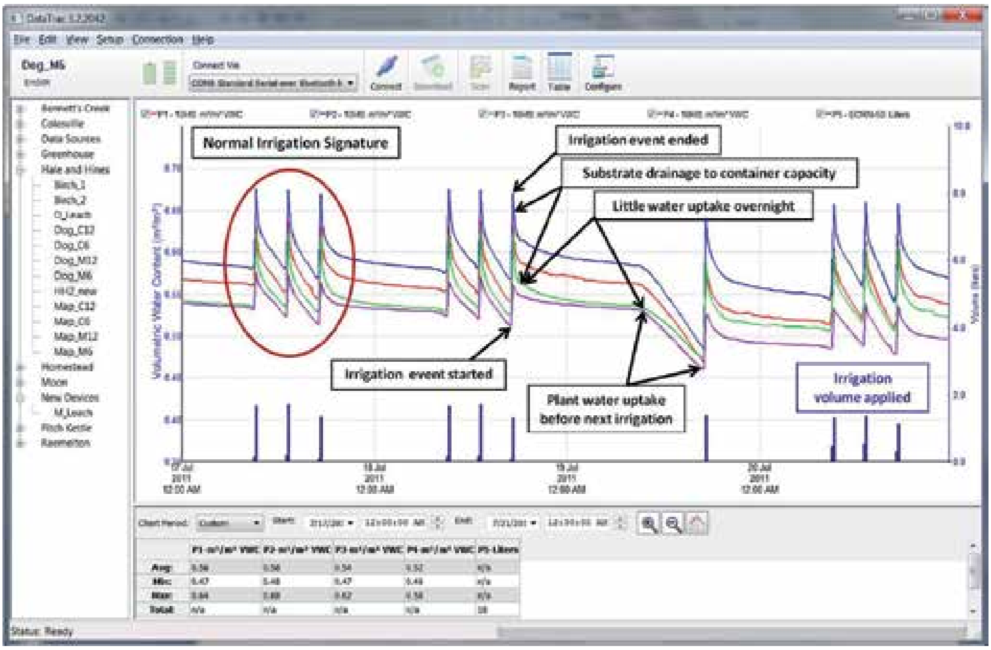


Fig. 3. Typical container moisture dynamics before and after irrigation events in four *Cornus florida* trees. Data is graphically displayed using the most recent version of DataTrac (v. 3.2).

3.4.2 Sensor placement

Changes in substrate VWC due to daily water use of a crop can be used to control irrigation events, but placement of sensors is very important in container production, because of the non-uniform distribution of water within a soilless substrate and container. van Iersel et al. (2011) illustrated this point, by calculating the *rate of change* in substrate VWC. They noted that the maximum rate of decrease in VWC occurred at the bottom of the container in a greenhouse study and closely followed changes in solar radiation, suggesting that changes in VWC were driven by root water uptake from the lower part of the container. However, the vertical gradient in substrate VWC also changed over time i.e., the VWC of the bottom layer decreased much more rapidly than that of the upper layers, likely because of the root distribution within the container. Apparently, the lack of roots in the upper part of the substrate resulted in little water uptake from that substrate layer, and vertical water movement in the container was not fast enough to prevent the middle layers from getting drier than the upper layer. If these findings can be generalized for other container-grown species, it would greatly increase our understanding for correct sensor placement in root zones, simplifying placement and increasing the precision of information for controlling irrigation events. However, since root distribution is affected by irrigation method, optimal placement of soil moisture sensors for irrigation control may depend on how the crop is irrigated (van Iersel et al., 2011).

Sensor placement is especially challenging for crops grown in large containers over relatively long periods of time. Barnard et al. (2011) examined the spatial and temporal variation in VWC among 10 tree species in large containers in a container nursery, and found significant differences within containers and among species. Based on their initial results, they recommended species-specific sensor deployment. For such crops, where root distribution within the container may change dramatically throughout the production period, it may be necessary to move the soil moisture sensor as root distribution changes, or it may be possible to use a soil moisture sensor that can sense the substrate water content throughout most of the container. It is therefore likely that a hybrid sensor and crop water use model approach will have greater degree of precision for automated irrigation scheduling, a feature desired by many greenhouse and container-nursery growers.

3.4.3 Using indicator plant species

For many ornamental operations, it is unlikely that we will be able to sense the water needs of all crop species being grown. Many growers however are familiar with the concept of using indicator species (i.e., species that have high and low water use, on average), which are used to inform irrigation schedules for similar types of plants (Yeager et al., 2007). For this reason, we are developing crop models which include a number of these indicator species in the decision support software. Part of this strategy is also to engage the larger research community in the development and incorporation of additional specific crop models (e.g. Warsaw et al., 2009) in future irrigation decision support systems.

3.4.4 Microclimatic data

The gathering and seamless integration of real-time environmental data is integral to the development and implementation of crop-specific (Bauerle et al., 2010; Kim and van Iersel, 2011) and environmental models (Starry, 2011). Typical microclimatic data which is gathered by “weather” nodes is displayed in Fig. 4. Tools within DataTrac v.3.2 now allow for the calculation and plotting of integrated data, such as vapor pressure deficit, daily light integral and accumulated degree days, as simple derivatives of this instantaneous data. Apart from the integration of this data into various crop, environmental and disease development models, this microclimatic data has many other direct practical benefits for producers, e .g. the use of real-time T/RH and wind speed data for precision timing of spray schedules in the field. Longer-term seasonal information for light, precipitation and maximum/minimum air and soil temperatures are very informative for growers to assess crop growth development and other production variables e.g. residual soil nutrient values.

3.4.5 Predictive irrigation scheduling

The integration of real-time microclimatic data into crop-specific and environmental water use models is the next step in our development path; we have successfully parameterized petunia (Kim and van Iersel, 2011), red maple (Bauerle et al., 2011b) and green roof

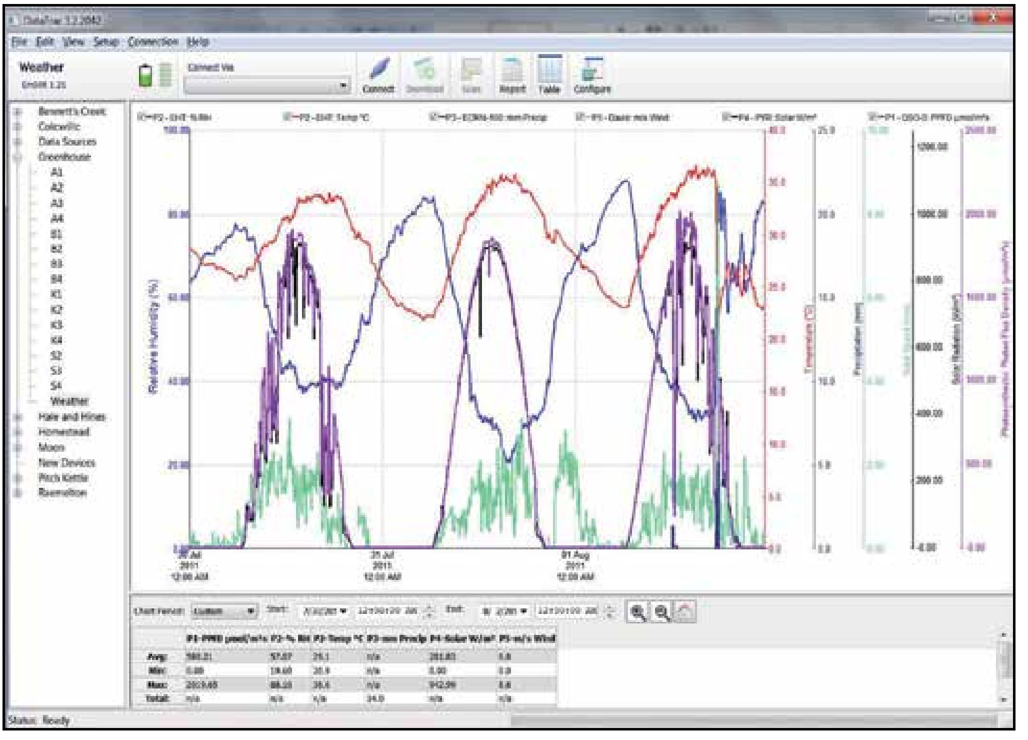


Fig. 4. Weather data from a sensor node with a typical suite of environmental sensors, including total radiation (black), photosynthetic photon flux (purple), relative humidity, RH (blue), air temperature, T (red) and wind speed (green).

stormwater runoff (Starry et al, 2011) models, and we are verifying and validating those models with current research projects. Our modeling and engineering teams are interfacing these models with a testbed sensorweb system (Kohanbash et al., 2011). In their paper, they present a framework for integrating physiological models into WSN for advanced irrigation scheduling. They note that the ability to gather high resolution data, interpret it, and create an actionable conclusion is a critical ability for a WSN.

Kohanbash et al. (2011) outlined our irrigation scheduling programming logic where growers create a schedule for when water needs to be applied, and then the schedule is interrupted as needed. This system provides growers with four operating modes: (1) a schedule-based controller very similar to what is commonly used in the industry. Within the schedule, there are two different options to over-ride the schedule to decrease the irrigation time (a) a local setpoint controller and (b) a global controller. The schedule + local setpoint controller enables the sensor node to make local control decisions based on sensors attached to the node. The schedule + global controller allows the grower to use data from *any* node in the network, calculated data or model data to control the irrigation and consequently determine if the schedule should be interrupted. The fourth mode is a manual override mode that allows the grower to water in traditional mode, for a given number of minutes. This irrigation scheduling flexibility gives a grower the ability to control how water gets applied to an irrigation zone, with various user-defined parameters. The user can choose between a mode where water will be applied slowly with small delays between irrigation events to allow water to reach subsurface sensors (micro-pulse irrigation; Lea-Cox et al., 2009) or a mode in which water is applied continuously for a specified period of time.

4. Challenges, opportunities and conclusions

Of course there are many areas where we need additional research and development, to provide the maximum cost benefit of WSNs for growers. Challenges include standardizing WSN protocols and communication frequencies, as they can be confusing for growers and researchers alike. Nodes operating at lower frequencies (900 MHz) typically have an increased range and can penetrate tree canopies better than higher frequency (2.4 GHz) nodes with reduced packet loss. Battery-operated nodes are typical; integrating rechargeable capabilities into sensor nodes is important, especially if control capabilities are going to become standard, since this will greatly increase power requirements. Another challenge is working with large datasets. We have to educate ourselves as to the resolution required for optimum precision in each environment, keeping the ultimate use of the data in mind.

The maintenance and calibration of sensors and equipment is an ongoing concern, particularly for growers who may be uncomfortable with the technology and equipment. We definitely see an opportunity for paid consultants to maintain and remotely monitor WSNs for optimum performance. As part of our project, we are developing an online knowledge center, to provide assistance and guidance about various aspects of WSN deployment, sensor use, strategies and best practices. We need to integrate better data analysis tools to handle large volumes of data from sensor networks. We also need to do a thorough user interface study on how growers actually use computer interfaces and to determine what features are needed. Predictive models for plant water use, environmental and disease management tools are rapidly being developed for growers, but we need to validate and verify these models for use in different environments. Incorporation of models into WSNs for decision-making appears to be relatively easy, but there are many details which have yet to be worked out.

There are many layers to the socio-economic analysis our economic team is performing. Of course there are many direct benefits of precision irrigation scheduling that can be accrued by the grower, such as saving on water, labor, electricity, and fertilizer costs. However, there are many indirect (e.g. reduced disease incidence, fungicide costs) and societal benefits (reduced nutrient runoff, groundwater consumption) that may have much larger benefits over the long-term for all agricultural producers. Most importantly, we need to quantify the return on investment that a grower could expect to achieve, and to be able to scale those benefits for small producers, along with scaling WSN deployments. We are also interested in documenting perceived and real barriers to adoption. Our socio-economic team is actively surveying a large number of growers with a detailed survey, to compare the use of sensor technology and irrigation decisions by early and late adopters.

In conclusion, we believe that there have been some real advances in WSNs for precision irrigation scheduling in recent years. Of course many challenges still remain, but we believe that WSNs are a fast-maturing technology that will be rapidly adopted by many growers in the near future.

5. Acknowledgements

We gratefully acknowledge grant support from the USDA-NIFA Specialty Crops Research Initiative Award # 2009-51181-05768. I would like to thank Bill Bauerle, Marc van Iersel, David Kohanbash and Bruk Belayneh for their excellent reviews which improved this Chapter. I would also like to personally acknowledge the dedication and talent of everyone on this project, without whom none of this research and development would be possible.

6. References

Anastasiou, A., Savvas, D., Pasgianos, G., Stangellini. C., Kempkes, F. & Sigrimis, N. 2008. Decision Support for Optimised Irrigation Scheduling. *Acta Hort.* 807:253–258.

Agarwal, A., delos Angeles, M.S., Bhatia, R., Cheret, I., Davila-Poblete, S., Falkenmark, M., Gonzalez Villarreal, F., Jønch-Clausen, T., Kadi, M.A., Kindler, J., Rees, J., Roberts, P., Rogers, P., Solanes, M. & Wright. A. 2000. Integrated Water Resources Management. *Global Water Partnership*. Denmark.

Akyildiz, I.F., Su, W., Sankarasubramaniam, Y. & Cayirci, E. 2002. Wireless Sensor Networks: A Survey. *Computer Networks 38*:393-422.

Allen, R. G., Pereira, L. S., Raes, D. & Smith. M. 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. *FAO Irrigation and drainage paper no.56.* FAO, Rome, Italy.

Bacci, L., Battista, P. and Rapi, B. 2008. An Integrated Method for Irrigation Scheduling of Potted Plants. *Sci. Hortic.* 116:89-97.

Bauerle, W.L., Post, C.J., McLeod, M.E., Dudley J.B. & Toler, J.E. 2002. Measurement and Modeling of the Transpiration of a Temperate Red Maple Container Nursery. *Agric. For. Meteorol.* 114:45-57.

Bauerle, W.L., Bowden, J.D., McLeod M.F. & Toler, J.E. 2004. Modeling Intracrown and Intracanopy Interactions in Red Maple: Assessment of light transfer on carbon dioxide and water vapor exchange. *Tree Physiol*. 24:589-597.

Bauerle, W.L., Timlin, D.J., Pachepsky, Ya.A. & Anantharamu., S. 2006. Adaptation of the Biological Simulation Model MAESTRA for Use in a Generic User Interface. *Agron. J.* 98:220-228.

Bauerle, W.L. & Bowden, J.D. 2011a. Predicting Transpiration Response to Climate Change: Insights on Physiological and Morphological Interactions that Modulate Water Exchange from Leaves to Canopies. *HortScience* 46:163-166.

Bauerle, W.L. & Bowden, J.D. 2011b. Separating Foliar Physiology from Morphology Reveals the Relative Roles of Vertically Structured Transpiration Factors Within Red Maple Crowns and Limitations of Larger Scale Models. *J. Exp. Bot.* 62:4295-4307.

Balendonck, J., Stanghellini, C., & Hemming, J. 2007. Farm Level Optimal Water Management: Assistant for Irrigation under Deficit (FLOW-AID). *In: Water Saving in Mediterranean Agriculture & Future Research Needs*, Bari, Italy, Lamaddalena N. & Bogliotti, C. (Eds.), CIHEAM, Bari, Italy. pp. 301-312.

Balendonck, J., Stanghellini, C., Hemming, J., Kempkes F.L.K. & van Tuijl, B.A.J. 2009. Farm Level Optimal Water Management: Assistant for Irrigation under Deficit (FLOW-AID). *Acta Hort* 807: 247-252.

Barnard, D.M, Daniels, A.B. & Bauerle, W.L., 2011. Optimizing Substrate Moisture Measurements in Containerized Nurseries: Insights on Spatial and Temporal Variability. *HortScience* 46(9): S207. (Abstr.)

Barrenetxea, G., Ingelrest, F., Schaefer, G., & Vetterli, M. 2008. The Hitchhiker's Guide to Successful Wireless Sensor Network Deployments. *In: Proc. 6th ACM Int. Conf. Embedded Networked Sensor Systems (SenSys)* Raleigh, NC, Nov. 5 -7, 2008. pp. 43-56.

Beeson Jr., R.C. & Brooks. J. 2008. Evaluation of a Model Based and Reference Crop Evapotranspiration (ETo) for Precision Irrigation using Overhead Sprinklers during Nursery Production of *Ligustrum japonica*. *Acta Hort.* 792:85-90.

Bitelli, M. 2011. Measuring Soil Water Content: A Review. *HortTechnology* 21: 293-300.

Blonquist, J.J.M., Jones, S.B. & Robinson. D.A. 2006. Precise Irrigation Scheduling for Turfgrass using a Subsurface Electromagnetic Soil Moisture Sensor. *Agricultural Water Management* 84:153-165.

Bowden, J.D. & Bauerle, W.L. 2008. Measuring and Modeling the Variation in Species-Specific Transpiration in Temperate Deciduous Hardwoods. *Tree Physiol.* 28:1675–1683.

Bowden, J. D., Bauerle, W.L., Lea-Cox, J.D. & Kantor, G.F. 2005. Irrigation Scheduling: An Overview of the Potential to Integrate Modeling and Sensing Techniques in a Windows-based Environment. *Proc. Southern Nursery Assoc. Res. Conf.* 50:577-579.

Bunt, A.C. 1961. Some Physical Properties of Pot-Plant Composts and their Effect on Plant Growth. *Plant and Soil* 13:322-332.

Burger, D.W. & Paul, J.L. 1987. Soil Moisture Measurements in Containers with Solid State, Electronic Tensiometers. *HortScience* 22:309-310.

Burnett, S.E. & van Iersel, M.W. 2008. Morphology and Irrigation Efficiency of *Gaura Lindheimeri* Grown with Capacitance-Sensor Controlled Irrigation. *HortScience* 43:1555-1560.

Campbell, G. S. & Norman. J. 1998. An Introduction to Environmental Biophysics. 2nd Ed. *Springer* New York, NY.

Cifre, J., Bota, J., Escalona, J.M., Medrano, H. & Flexas, J. 2005. Physiological Tools for Irrigation Scheduling in Grapevine (*Vitis vinifera* L.). *Agric. Ecosys. Environ*. 106:159-170.

Christmann, A., Weiler, E.W., Steudle, E. & Grill. E. 2007. A Hydraulic Signal in Root-to-Shoot Signaling of Water Shortage. *Plant J.* 52:167-174.

Dane, J.H. & Topp, G.C. 2002. Methods of Soil Analysis. Part 4: Physical Methods. *Amer. Soc. Soil Sci.*, Madison, WI.

deBoodt, M. & O. Verdonck. 1972. The Physical Properties of Substrates in Horticulture. *Acta Hort*. 26:37-44.

Ferentinos, K.P., Anastasiou, A., Pasgianos, G.D., Arvanitis, K.G. & Sigrimis, N. 2003. A DSS as a Tool to Optimal Water Management in Soilless Cultures under Saline Conditions. *Acta Hort.* 609:289-296.

Fereres, E.; Goldhamer, D.A. & Parsons, L.R. 2003. Irrigation Water Management of Horticultural Crops. *HortScience* 38:1036-1042.

Fereres, E. & Goldhamer, D.A. 2003. Suitability of Stem Diameter Variations and Water Potential as Indicators for Irrigation Scheduling of Almond Trees. *J. Hort. Sci Biotech.* 78:139–144.

Fry, A., 2005. Facts and Trends, Water. *World Business Council for Sustainable Development, Earthprint Ltd.* ISBN 2-940240-70-1.

Guimerà, J. 1998. Anomalously High Nitrate Concentrations in Ground Water. *GroundWater* 36:275–282.

Handreck, K. & Black. N. 2002. Growing Media for Ornamental Plants and Turf (3rd Ed.). *Univ. New South Wales Press*, Sydney, Australia.

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S. & Maupin, M.A. 2004. Estimated Use of Water in the United States in 2000. *Circular* 1268. *U.S. Geological Survey*, U.S. Dept. Interior. Reston, VA.

Jones, H.G. 1992. Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology. (2nd ed.) *Cambridge University Press*. Cambridge. UK.

Jones, H.G. 1990. Physiological-Aspects of the Control of Water Status in Horticultural Crops. *HortScience* 25: 19–26.

Jones, H.G. 2004. Irrigation Scheduling: Advantages and Pitfalls of Plant-Based Methods. J. Exp. Bot. 55:2427-2436.

Jones, H.G. 2008. Irrigation Scheduling - Comparison of Soil, Plant and Atmosphere Monitoring Approaches. *Acta Hort*. 792: 391-403.

Jones, H.G. & Tardieu F. 1998. Modeling Water Relations of Horticultural Crops: A Review. *Scientia Horticulturae*. 74:21–46.

Karlovich, P.T. & Fonteno, W.C. 1986. The Effect of Soil Moisture Tension and Volume Moisture on the Growth of *Chrysanthemum* in Three Container Media. *J. Amer. Soc. Hort. Sci.* 111:191-195.

Kiehl, P.A., Liel, J.H. & Buerger, D.W. 1992. Growth Response of *Chrysanthemum* to Various Container Medium Moisture Tensions Levels. *J. Amer. Soc. Hort. Sci.* 117:224-229.

Kim, Y., Evans, R.G. & Iversen, W.M. 2008. Remote Sensing and Control of an Irrigation System using a Distributed Wireless Sensor Network. *IEEE Trans. Instrum. Meas. 57*:1379-1387.

Kim, J. & van Iersel, M.W. 2009. Daily Water Use of Abutilon and Lantana at Various Substrate Water Contents. *Proc. Southern Nursery Assn. Res. Conf*. 54:12-16.

Kim, J., van Iersel, M.W. & Burnett, S.E. 2011. Estimating Daily Water Use of Two Petunia Cultivars Based on Plant and Environmental Factors. *HortScience* 46:1287-1293.

Kim, J. & van Iersel. M.W. 2011. Abscisic Acid Drenches can Reduce Water Use and Extend Shelf Life of *Salvia splendens*. *Sci. Hort.* 127: 420–423.

Kohanbash D., Valada, A. & Kantor, G.F. 2011. Wireless Sensor Networks and Actionable Modeling for Intelligent Irrigation. *Amer. Soc. Agric. Biol. Eng*. 7-12th August, 2011. Louisville, KY. Paper #1111174. 7p.

Lea-Cox, J.D., Ross, D.S. and Teffeau, K.M. 2001. A Water And Nutrient Management Planning Process For Container Nursery And Greenhouse Production Systems In Maryland. *J. Environ. Hort.* 19:230-236.

Lea-Cox, J. D., Arguedas-Rodriguez, F. R., Amador, P., Quesada, G. & Mendez, C.H. 2006. Management of the Water Status of a Gravel Substrate by Ech20 Probes to Reduce *Rhizopus* Incidence in the Container Production of *Kalanchoe blossfeldiana. Proc. Southern Nursery Assoc. Res. Conf.* 51: 511-517.

Lea-Cox, J. D., Kantor, G. F., Anhalt, J., Ristvey A.G. & Ross. D.S. 2007. A Wireless Sensor Network for the Nursery and Greenhouse Industry. *Proc. Southern Nursery Assoc. Res. Conf.* 52: 454-458.

Lea-Cox, J.D., Ristvey, A.G. Arguedas-Rodriguez, F.R., Ross, D.S., Anhalt J. & Kantor. G.F. 2008. A Low-cost Multihop Wireless Sensor Network, Enabling Real-Time Management of Environmental Data for the Greenhouse and Nursery Industry. *Acta Hort.* 801:523-529.

Lea-Cox, J.D., Black, S., Ristvey A.G. & Ross. D.S. 2008. Towards Precision Scheduling of Water and Nutrient Applications, Utilizing a Wireless Sensor Network on an Ornamental Tree Farm. *Proc. Southern Nursery Assoc. Res. Conf.* 53: 32-37.

Lea-Cox, J.D., Ristvey, A.G., Ross, D.S. & Kantor. G.F. 2009. Deployment of Wireless Sensor Networks for Irrigation and Nutrient Management in Nursery and Greenhouse Operations. *Proc. Southern Nursery Assoc. Res. Conf.* 54: 28-34.

Lea-Cox, J.D., Kantor, G.F., Bauerle, W.L., van Iersel, M.W., Campbell, C., Bauerle, T.L., Ross, D.S., Ristvey, A.G., Parker, D., King, D., Bauer, R., Cohan, S. M., Thomas, P. Ruter, J.M., Chappell, M., Lefsky, M., Kampf, S. & L. Bissey. 2010a. A Specialty Crops Research Project: Using Wireless Sensor Networks and Crop Modeling for Precision Irrigation and Nutrient Management in Nursery, Greenhouse and Green Roof Systems. *Proc. Southern Nursery Assoc. Res. Conf. 55*: 211-215.

Lea-Cox, J.D., Kantor, G.F., Bauerle, W.L., van Iersel, M.W., Campbell, C., Bauerle, T.L., Parker, D., King, D., Bauer, R., L. Bissey & Martin, T. 2010b. SCRI-MINDS-Precision Irrigation and Nutrient Management in Nursery, Greenhouse and Green Roof Systems: Year 1 Report. Available from <http://www.smart-farms.net/impacts> Accessed 08/02/2011.

Lea-Cox, J.D., Arguedas-Rodriguez, F. R., Ristvey A. G. & Ross. D. S. 2011. Relating Real-time Substrate Matric Potential Measurements to Plant Water Use, for Precision Irrigation. *Acta Hort.* 891:201-208.

Leith, J.H. & Burger. D.W. 1989. Growth Of Chrysanthemum Using An Irrigation System Controlled By Soil Moisture Tension. *J. Amer. Soc. Hort. Sci.* 114: 387-397

Liu, G. & Ying, Y. 2003. Application Of Bluetooth Technology In Greenhouse Environment, Monitor And Control. *J. Zhejiang Univ., Agric Life Sci. 29*:329-334.

Majsztrik, J.C., A.G. Ristvey, and J.D. Lea-Cox. 2011. Water and Nutrient Management in the Production of Container-Grown Ornamentals. *Hort. Rev.* 38:253-296.

Murray, J.D., Lea-Cox J.D. & Ross. D.S. 2004. Time Domain Reflectometry Accurately Monitors and Controls Irrigation Water Applications *Acta Hort.* 633:75-82.

Nemali, K.S. & van Iersel, M.W. 2006. An Automated System for Controlling Drought Stress and Irrigation in Potted Plants. *Sci. Hortic.* 110:292-297.

Nobel, P.S. 2009. Physicochemical and Environmental Plant Physiology 4th Ed. *Elsevier Inc.* Waltham, MA.

O'Shaughnessy, S.A. & Evett, S.R. 2008. Integration of Wireless Sensor Networks into Moving Irrigation Systems for Automatic Irrigation Scheduling. *Amer. Soc. Agric. Biol. Eng.* 29 June - 2 July, 2008. Providence, RI. Paper # 083452, 21p.

Pieruschka, R., Huber, G. & Berry, J.A. 2010. Control of Transpiration by Radiation. *Proc. Natl. Acad. Sci.* 107:13372-13377.

Raviv, M., Lieth, J.H. & Wallach, R. 2000. Effect of Root-Zone Physical Properties of Coir and UC Mix on Performance of Cut Rose (cv. Kardinal). *Acta Hort.* 554:231-238.

Ristvey, A.G., Lea-Cox, J.D. & Ross, D.S. 2004. Nutrient Uptake, Partitioning And Leaching Losses From Container-Nursery Production Systems. *Acta Hort.* 630:321-328.

Ross, D. S., Lea-Cox, J.D. & Teffeau, K.M. 2001. The Importance of Water in the Nutrient Management Process. *Proc. Southern Nursery Assoc. Res. Conf.* 46:588-591.

Ruiz-Garcia, L., Lunadei, L., Barreiro, P. & Robla, J. I. 2009. A Review of Wireless Sensor Technologies and Applications in Agriculture and Food Industry: State of the Art and Current Trends. *Sensors* 9: 4728-4750.

Secchi, S., Gassman, P.W., Jha, M., Kurkalova, L., Feng, H.H., Campbell, T. & King. C.L. 2007. The Cost of Cleaner Water: Assessing Agricultural Pollution Reduction at The Watershed Scale. *J. Soil Water Conservation* 62:10–22.

Smith, K.A. & Mullins, C. 2001. Soil and Environmental Analysis: Physical Methods. 2nd Ed. *Marcel Decker*, New York, NY.

Smajstrla A.G. & Harrison, D.S. 1998. Tensiometers for Soil Moisture Measurement and Irrigation Scheduling. *Univ. Fl. IFAS Ext. Cir.* No. 487. 8p.

Stanghellini, C. & van Meurs., W.T.M., 1989. Crop Transpiration: A Greenhouse Climate Control Parameter. *Acta Hort.*, 245: 384-388.

Stanghellini, C., Pardossi, A. & Sigrimis, N. 2007. What Limits the Application of Wastewater and/or Closed Cycle in Horticulture? *Acta Hort.* 747:323-330.

Starry, O., Lea-Cox, J.D., Ristvey, A.G. & Cohan, S. 2011. Utilizing Sensor Networks to Assess Stormwater Retention by Greenroofs. *Amer. Soc. Agric. Biol. Eng.* 7-12th August, 2011. Louisville, KY. Paper #1111202, 7p.

Taiz, L. & Zeiger, E. 2006. Plant Physiology. *Sinauer Associates, Inc.* Sunderland, MA

Testezlaf, R., Larsen, C.A., Yeager, T.H. & Zazueta. F.S. 1999. Tensiometric Monitoring of Container Substrate Moisture Status. *HortTechnology* 9:105-109.

Treder, J., Matysiak,B., Nowak, J. & Treder, W. 1997. Evapotranspiration and Potted Plants Water Requirements as Affected by Environmental Factors. *Acta Hort.* 449:235-240.

Tolle, G., Polastre, J., Szewczyk, R., Culler, D., Turner, N., Tu, K., Burgess, S., Dawson, T., Buonadonna, P. Gay, D. & Hong. W. 2005. A Macroscope in the Redwoods. *In: Proc. 3rd ACM International Conference on Embedded Networked Sensor Systems* (SenSys), 2005. San Diego. Nov 2-4, 2005. pp. 51- 63.

Topp, G.C. 1985. Time-Domain Reflectometry (TDR) and its Application to Irrigation Scheduling. *Adv. Irr.* 3:107-127.

Tyler, H.H., Warren, S.L & Bilderback, T.E 1996. Cyclic Irrigation Increases Irrigation Application Efficiency and Decreases Ammonium Losses. *J. Environ. Hort.* 14:194–198.

United States Global Change Research Program. 2011. Overview: Water. Available from <http://www.globalchange.gov/component/content/article/52-reports-and-assessments/481-overview-water> Accessed 07/15/2011.

van Iersel, M.W. 2003. Short-Term Temperature Change Affects the Carbon Exchange Characteristics and Growth of Four Bedding Plant Species. *J. Amer. Soc. Hort. Sci.* 128:100-106.

van Iersel, M. W., Seymour, R.M., Chappell, M., Watson, F. & Dove, S. 2009. Soil Moisture Sensor-Based Irrigation Reduces Water Use and Nutrient Leaching in a Commercial Nursery. *Proc. Southern Nursery Assoc. Res. Conf.* 54:17-21.

van Iersel, M.W., Dove, S. Kang, J-G. & Burnett, S.E. 2010. Growth and Water Use of Petunia as Affected by Substrate Water Content and Daily Light Integral. *HortScience* 45:277-282.

van Iersel, M.W., Dove, S. & Burnett, S.E. 2011. The Use of Soil Moisture Probes for Improved Uniformity and Irrigation Control in Greenhouses. *Acta Hort.* 893:1049-1056.

Vellidis, G., Tucker, M., Perry, C., Wen, C. & Bednarz, C. 2008. A Real-Time Wireless Smart Sensor Array for Scheduling Irrigation. *Comput. Electron. Agric. 61*:44-50.

Wang, Y.P. & Jarvis. P.G. 1990. Description and Validation of an Array Model-MAESTRO. *Agricultural Forest Meteorology.* 51:257–280.

Wang, C., Zhao, C.J., Qiao, X.J., Zhang, X. & Zhang, Y.H. 2008. The Design of Wireless Sensor Networks Node for Measuring the Greenhouse's Environment Parameters. *Computing. Technol. Agric. 259*:1037-1046.

Warsaw, A. L., Fernandez, R. T., Cregg, B. M. & Andresen. J. A. 2009. Water Conservation, Growth, and Water Use Efficiency of Container-Grown Woody Ornamentals Irrigated Based on Daily Water Use. *HortScience* 44: 1308-1318.

Yeager, T.H., Bilderback, T.E., Fare, D., Gilliam, C., Lea-Cox, J.D., Niemiera, A.X., Ruter, J.M., Tilt, K., Warren, S.L., Whitwell T. & Wright. R.D. 2007. Best Management Practices: Guide for Producing Nursery Crops. 2nd Ed. *Southern Nursery Assoc.*, Atlanta, GA.

Yoo, S., Kim, J., Kim, T., Ahn, S., Sung, J. & Kim, D. 2007. A2S: Automated Agriculture System Based on WSN. *In: ISCE 2007. IEEE International Symposium on Consumer Electronics.* Irving, TX, USA.

Zazueta, F.S., Yeager, T., Valiente, J.I. & Brealey, J.A. 1994. A Modified Tensiometer for Irrigation Control in Potted Ornamental Production. *Proc. Soil Crop Sci. Soc. Fla.* 53:36-39.

13

Comparison of Different Irrigation Methods Based on the Parametric Evaluation Approach in West North Ahwaz Plain

Mohammad Albaji[1], Saeed Boroomand Nasab[1] and Jabbar Hemadi [2]
[1]*Irrigation and Drainage Dept., Faculty of Water Sciences Eng.*
Shahid Chamran University, Ahwaz
[2]*Khuzestan Water & Power Authority, Ahwaz*
Iran

1. Introduction

Food security and stability in the world greatly depends on the management of natural resources. Due to the depletion of water resources and an increase in population, the extent of irrigated area per capita is declining and irrigated lands now produce 40% of the food supply (Hargreaves and Mekley.1998). Consequently, available water resources will not be able to meet various demands in the near future and this will inevitably result into the seeking of newer lands for irrigation in order to achieve sustainable global food security. Land suitability, by definition, is the natural capability of a given land to support a defined use. The process of land suitability classification is the appraisal and grouping of specific areas of land in terms of their suitability for a defined use.

According to FAO methodology (1976) land suitability is strongly related to "land qualities" including erosion resistance, water availability, and flood hazards which are in themselves immeasurable qualities. Since these qualities are derived from "land characteristics", such as slope angle and length, rainfall and soil texture which are measurable or estimable, it is advantageous to use the latter indicators in the land suitability studies, and then use the land parameters for determining the land suitability for irrigation purposes. Sys et al. (1991) suggested a parametric evaluation system for irrigation methods which was primarily based upon physical and chemical soil properties. In their proposed system, the factors affecting soil suitability for irrigation purposes can be subdivided into four groups:

- Physical properties determining the soil-water relationship in the soil such as permeability and available water content;
- Chemical properties interfering with the salinity/alkalinity status such as soluble salts and exchangeable Na;
- Drainage properties;
- Environmental factors such as slope.

Briza et al. (2001) applied a parametric system (Sys et al. 1991) to evaluate land suitability for both surface and drip irrigation in the Ben Slimane Province, Morocco, while no highly suitable areas were found in the studied area. The largest part of the agricultural areas was classified as marginally suitable, the most limiting factors being physical parameters such as slope, soil calcium carbonate, sandy soil texture and soil depth.

Bazzani and Incerti (2002) also provided a land suitability evaluation for surface and drip irrigation systems in the province of Larche, Morocco, by using parametric evaluation systems. The results showed a large difference between applying the two different evaluations. The area not suitable for surface irrigation was 29.22% of total surface and 9% with the drip irrigation while the suitable area was 19% versus 70%. Moreover, high suitability was extended on a surface of 3.29% in the former case and it became 38.96% in the latter. The main limiting factors were physical limitations such as the slope and sandy soil texture.

Bienvenue et al. (2003) evaluated the land suitability for surface (gravity) and drip (localized) irrigation in the Thies, Senegal, by using the parametric evaluation systems. Regarding surface irrigation, there was no area classified as highly suitable (S_1). Only 20.24% of the study area proved suitable (S_2, 7.73%) or slightly suitable (S_3, 12. 51%). Most of the study area (57.66%) was classified as unsuitable (N_2). The limiting factor to this kind of land use was mainly the soil drainage status and texture that was mostly sandy while surface irrigation generally requires heavier soils. For drip (localized) irrigation, a good portion (45.25%) of the area was suitable (S_2) while 25.03% was classified as highly suitable (S_1) and only a small portion was relatively suitable (N_1, 5 .83 %) or unsuitable (N_2, 5.83%). In the latter cases, the handicap was largely due to the shallow soil depth and incompatible texture as a result of a large amount of coarse gravel and/or poor drainage.

Mbodj et al. (2004) performed a land suitability evaluation for two types of irrigation i. e, surface irrigation and drip irrigation, in the Tunisian Oued Rmel Catchment using the suggested parametric evaluation. According to the results, the drip irrigation suitability gave more irrigable areas compared to the surface irrigation practice due to the topographic (slope), soil (depth and texture) and drainage limitations encountered with in the surface irrigation suitability evaluation.

Barberis and Minelli (2005) provided land suitability classification for both surface and drip irrigation methods in Shouyang county, Shanxi province, China where the study was carried out by a modified parametric system. The results indicated that due to the unusual morphology, the area suitability for the surface irrigation (34%) is smaller than the surface used for the drip irrigation (62%). The most limiting factors were physical parameters including slope and soil depth.

Dengize (2006) also compared different irrigation methods including surface and drip irrigation in the pilot fields of central research institute, lkizce research farm located in southern Ankara. He concluded that the drip irrigation method increased the land suitability by 38% compared to the surface irrigation method. The most important limiting factors for surface irrigation in study area were soil salinity, drainage and soil texture, respectively whereas, the major limiting factors for drip or localized irrigation were soil salinity and drainage.

Liu et al. (2006) evaluated the land suitability for surface and drip irrigation in the Danling County, Sichuan province, China, using a Sys's parametric evaluation system. For surface irrigation the most suitable areas (S_1) represented about (24%) of Danling

County, (33%) was moderately suitable (S_2), (%9) was classified as marginally suitable (S_3), (7%) of the area was founded currently not suitable (N_1) and (25%) was very unsuitable for surface irrigation due to their high slope gradient. Drip irrigation was everywhere more suitable than surface irrigation due to the minor environmental impact that it caused. Areas highly suitable for this practice covered 38% of Danling County; about 10% was marginally suitable (the steep dip slope and the structural rolling rises of the Jurassic period). The steeper zones of the study area (23%) were either approximately or totally unsuitable for such a practice.

Albaji et al. (2007) carried out a land suitability evaluation for surface and drip Irrigation in the Shavoor Plain, in Iran. The results showed that 41% of the area was suitable for surface irrigation ;50% of the area was highly recommend for drip irrigation and the rest of the area was not considered suitable for either irrigation method due to soil salinity and drainage problem.

Albaji et al. (2010a) compared the suitability of land for surface and drip irrigation methods according to a parametric evaluation system in the plains west of the city of Shush, in the southwest Iran. The results indicated that a larger amount of the land (30,100 ha—71.8%) can be classified as more suitable for drip irrigation than surface irrigation.

Albaji et al. (2010b) investigated different irrigation methods based upon a parametric evaluation system in an area of 29,300 ha in the Abbas plain located in the Elam province, in the West of Iran. The results demonstrated that by applying sprinkler irrigation instead of surface and drip irrigation methods, the arability of 21,250 ha (72.53%) in the Abbas plain will improve.

Albaji et al. (2010c) also provided a land suitability evaluation for surface, sprinkle and drip irrigation systems in Dosalegh plain: Iran. The comparison of the different types of irrigation techniques revealed that the drip and sprinkler irrigations methods were more effective and efficient than that of surface irrigation for improved land productivity. However, the main limiting factor in using either surface or/and sprinkler irrigation methods in this area were soil texture, salinity, and slope, and the main limiting factor in using drip irrigation methods were the calcium carbonate content, soil texture and salinity.

Albaji and Hemadi (2011) evaluated the land suitability for different irrigation systems based on the parametric evaluation approach on the Dasht Bozorg Plain:Iran. The results showed that by applying sprinkle irrigation instead of drip and surface irrigation, the arability of 1611.6 ha (52.5%) on the Dasht Bozorg Plain will improve. In addition, by applying drip irrigation instead of sprinkle or surface irrigation, the land suitability of 802.4 ha (26.2%) on this plain will improve. Comparisons of the different types of irrigation systems revealed that sprinkle and drip irrigation were more effective and efficient than surface irrigation for improving land productivity. It is noteworthy, however, that the main limiting factor in using sprinkle and/or drip irrigation in this area is the soil calcium carbonate content and the main limiting factors in using surface irrigation are soil calcium carbonate content together with drainage.

The main objective of this research is to evaluate and compare land suitability for surface, sprinkle and drip irrigation methods based on the parametric evaluation systems for the West North Ahwaz Plain, in the Khuzestan Province, Iran.

2. Materials and methods

The present study was conducted in an area about 37324.91 hectares in the West north ahwaz Plain, in the Khuzestan Province, located in the West of Iran during 2009-2011. The study area is located 5 km West north of the city of Ahwaz, 31° 20´ to 31 ° 40´ N and 48 ° 36´ to 48° 47´ E. The Average annual temperature and precipitation for the period of 1965-2004 were 24.5 C° and 210 mm, respectively. Also, the annual evaporation of the area is 2,550 mm (Khuzestan Water & Power Authority [KWPA], 2005). The Karun River supplies the bulk of the water demands of the region. The application of irrigated agriculture has been common in the study area. Currently, the irrigation systems used by farmlands in the region are furrow irrigation, basin irrigation and border irrigation schemes.

The area is composed of two distinct physiographic features i.e. River Alluvial Plains and Plateaux, of which the River Alluvial Plains physiographic unit is the dominating features. Also, twenty two different soil series were found in the area (Table.1).

The semi-detailed soil survey report of the West north ahwaz plain (KWPA. 2009) was used in order to determine the soil characteristics. Table.2 has shown some of physico – chemical characteristics for reference profiles of different soil series in the plain. The land evaluation was determined based upon topography and soil characteristics of the region. The topographic characteristics included slope and soil properties such as soil texture, depth, salinity, drainage and calcium carbonate content were taken into account. Soil properties such as cation exchange capacity (CEC), percentage of basic saturation (PBC), organic mater (OM) and pH were considered in terms of soil fertility. Sys et al. (1991) suggested that soil characteristics such as OM and PBS do not require any evaluation in arid regions whereas clay CEC rate usually exceeds the plant requirement without further limitation, thus, fertility properties can be excluded from land evaluation if it is done for the purpose of irrigation.

Based upon the profile description and laboratory analysis, the groups of soils that had similar properties and were located in a same physiographic unit, were categorized as soil series and were taxonomied to form a soil family as per the Keys to Soil Taxonomy (2008). Ultimately, twenty two soil series were selected for the surface, sprinkle and drip irrigation land suitability.

In order to obtain the average soil texture, salinity and $CaCo_3$ for the upper 150cm of soil surface, the profile was subdivided into 6 equal sections and weighting factors of 2, 1.5, 1, 0.75, 0.50 and 0.25 were used for each section, respectively (Sys et al.1991).

For the evaluation of land suitability for surface, sprinkle and drip irrigation, the parametric evaluation system was used (Sys et al. 1991). This method is based on morphology, physical and chemical properties of soil.

Six parameters including slope, drainage properties, electrical conductivity of soil solution, calcium carbonates status, soil texture and soil depth were also considered and rates were assigned to each as per the related tables, thus, the capability index for irrigation (Ci) was developed as shown in the equation (1):

$$Ci = A \times \frac{B}{100} \times \frac{C}{100} \times \frac{D}{100} \times \frac{E}{100} \times \frac{F}{100} \quad (1)$$

where A, B, C, D, E, and F are soil texture rating, soil depth rating, calcium carbonate content rating, electrical conductivity rating, drainage rating and slope rating, respectively.

Series No	Characteristics description
1	Soil texture " Heavy : *CL", without salinity and alkalinity limitation, Depth 150 cm, level to very gently sloping : 0 to 2%, imperfectly drained.
2	Soil texture " Heavy : CL", very severe salinity and alkalinity limitation, Depth 100 cm, level to very gently sloping : 0 to 2%, poorly drained.
3	Soil texture " Medium : SL", without salinity and alkalinity limitation, Depth 150 cm, level to very gently sloping : 0 to 2%, moderately drained.
4	Soil texture " Heavy : SIC", without salinity and alkalinity limitation, Depth 120 cm, level to very gently sloping : 0 to 2%, imperfectly drained.
5	Soil texture " Medium : SL", without salinity and alkalinity limitation, Depth 150 cm, level to very gently sloping : 0 to 2%, moderately drained.
6	Soil texture " Very Heavy: C", slight salinity and alkalinity limitation, Depth 125 cm, level to very gently sloping : 0 to 2%, poorly drained.
7	Soil texture " Very Heavy : SIC", very severe salinity and alkalinity limitation , Depth 140cm, level to very gently sloping : 0 to 2%, very poorly drained.
8	Soil texture" Very Heavy: C", severe salinity and alkalinity limitation, Depth 150cm, level to very gently sloping : 0 to 2%, very poorly drained.
9	Soil texture" Heavy: SICL", without salinity and alkalinity limitation, Depth 110 cm, level to very gently sloping : 0 to 2%, poorly drained.
10	Soil texture" Very Heavy: C", severe salinity and alkalinity limitation, Depth 150 cm, level to very gently sloping : 0 to 2%, very poorly drained.
11	Soil texture " Very Heavy : C", very severe salinity and alkalinity limitation, Depth 110 cm, level to very gently sloping : 0 to 2%, very poorly drained.
12	Soil texture " Medium : L", without salinity and alkalinity limitation, Depth 170 cm, level to very gently sloping : 0 to 2%, moderately drained.
13	Soil texture " Heavy : SICL", without salinity and alkalinity limitation, Depth 150 cm, level to very gently sloping : 0 to 2%, well drained.
14	Soil texture " Very Heavy : SIC", moderate salinity and alkalinity limitation, Depth 150 cm, level to very gently sloping : 0 to 2%, imperfectly drained.
15	Soil texture " Heavy: SICL", without salinity and alkalinity limitation, Depth 135 cm, level to very gently sloping : 0 to 2%, well drained.
16	Soil texture" Heavy: SICL",very without salinity and alkalinity limitation, Depth 150cm, level to very gently sloping : 0 to 2%, well drained.
17	Soil texture" Heavy: SCL", without salinity and alkalinity limitation, Depth 150 cm, level to very gently sloping : 0 to 2%, well drained.
18	Soil texture " Medium: SIL", slight salinity and alkalinity limitation, Depth 135 cm, level to very gently sloping : 0 to 2%, well drained.
19	Soil texture " Heavy : SICL", without salinity and alkalinity limitation , Depth 140cm, level to very gently sloping : 0 to 2%, well drained.
20	Soil texture" Heavy: SICL", without salinity and alkalinity limitation, Depth 150cm, level to very gently sloping : 0 to 2%, well drained.
21	Soil texture " Medium : SIL", slight salinity and alkalinity limitation, Depth 140 cm, level to very gently sloping : 0 to 2%, well drained.
22	Soil texture " Heavy : SICL", slight salinity and alkalinity limitation, Depth 130 cm, level to very gently sloping : 0 to 2%, well drained.

* Texture symbols: LS: Loamy Sand, SL: Sandy Loam, L: Loam , SIL: Silty Loam , CL: Clay Loam , SICL: Silty Clay Loam , SCL: Sandy Clay Loam , SC: Sandy Clay , SIC: Silty Clay , C: Clay.

Table 1. Soil series of the study area.

Soil seris.No	Soil seris.name	Depth (Cm)	Soil texture	ECe (ds.m-1)	pH	OM (%)	CEC (meq/100g)	$CaCo_3$ (%)
1	Veyss	150	CL	1.50	7.90	0.24	8.54	48.00
2	Omel Gharib	100	CL	48.00	7.70	0.46	5.61	49.00
3	Ramin	150	SL	1.10	7.80	0.39	8.19	41.00
4	Amerabad	120	SIC	3.50	8.50	0.23	10.31	48.00
5	Solieh	150	SL	3.40	7.90	0.29	5.57	34.00
6	Band Ghir	125	C	4.10	8.00	0.52	15.24	35.00
7	Abu Baghal	140	SIC	52.00	8.10	0.37	11.43	45.00
8	Sheykh Mussa	150	C	17.50	8.40	0.56	13.26	46.00
9	Safak	110	SICL	3.90	8.10	0.47	13.53	40.00
10	Molla Sani	150	C	21.50	7.90	0.36	12.91	39.00
11	Teal Bomeh	110	C	55.00	7.90	0.68	9.85	49.00
12	Karkheh	170	L	2.70	7.70	0.29	6.49	46.00
13	Karun 1	150	SICL	2.20	7.70	0.25	9.21	47.00
14	Shoteyt	150	SIC	9.50	7.90	0.60	8.66	47.00
15	Abbasieh 1	140	SICL	1.10	7.60	0.39	8.63	51.00
16	Deylam 1	150	SICL	2.90	7.50	0.28	10.48	50.00
17	Qalimeh	150	SCL	1.20	7.90	0.26	12.05	49.00
18	Abbasieh 2	135	SIL	5.90	7.60	0.39	12.73	44.00
19	Karun 2	140	SICL	1.00	7.60	0.41	10.22	51.00
20	Deylam 2	150	SICL	3.40	7.50	0.32	10.81	49.00
21	Ghaleh Nasir	140	SIL	4.20	7.60	0.38	11.56	51.00
22	Abdul Amir	130	SICL	7.50	7.80	0.57	10.38	46.00

Table 2. Some of physico – chemical characteristics for reference profiles of different soil series.

In Table 3 the ranges of capability index and the corresponding suitability classes are shown.

Capability Index	Definition	Symbol
> 80	Highly Suitable	S1
60-80	Moderately Suitable	S2
45-59	Marginally Suitable	S3
30-44	Currently Not Suitable	N1
< 29	Permanently Not Suitable	N2

Table 3. Suitability Classes for the Irrigation Capability Indices (Ci) Classes.

In order to develop land suitability maps for different irrigation methods (Figs.2-5), a semi-detailed soil map (Fig.1) prepared by Albaji was used, and all the data for soil characteristics were analyzed and incorporated in the map using ArcGIS 9.2 software.

The digital soil map base preparation was the first step towards the presentation of a GIS module for land suitability maps for different irrigation systems. The Soil map was then digitized and a database prepared. A total of twenty two different polygons or land mapping units (LMU) were determined in the base map. Soil characteristics were also given for each LMU. These values were used to generate the land suitability maps for surface, sprinkle and drip irrigation systems using Geographic Information Systems.

3. Results and discussion

Over much of the West north ahwaz Plain, the use of surface irrigation systems has been applied specifically for field crops to meet the water demand of both summer and winter crops .The major irrigated broad-acre crops grown in this area are wheat, barley, and maize, in addition to fruits , melons, watermelons and vegetables such as tomatoes and cucumbers. There are very few instances of sprinkle and drip irrigation on large area farms in the West north ahwaz Plain.

Twenty two soil series and eighty six series phases or land units were derived from the semi-detailed soil study of the area(Table.1). The land units are shown in Fig.1 as the basis for further land evaluation practice. The soils of the area are of Aridisols and Entisols orders. Also, the soil moisture regime is Aridic and Aquic while the soil temperature regime is Hyperthermic (KWPA.2003).

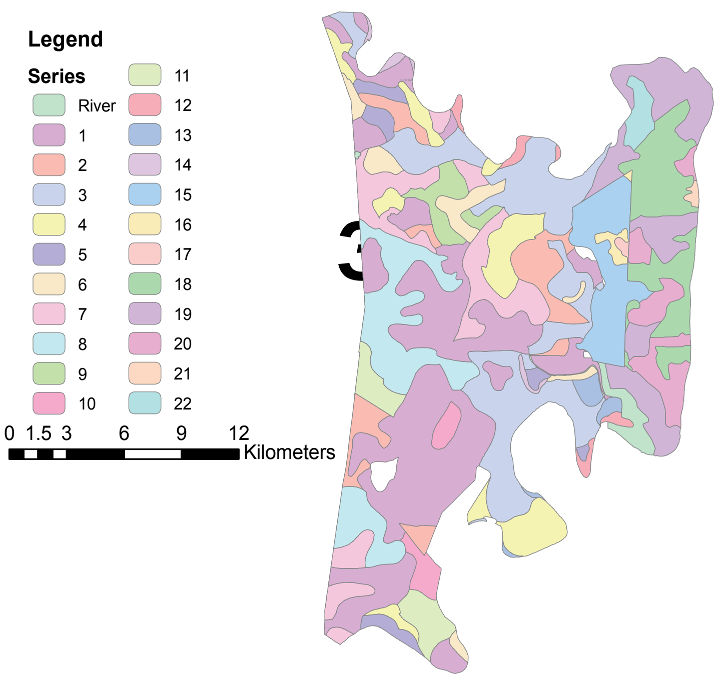


Fig. 1. Soil Map of the Study Area.

As shown in Tables 4 and 5 for surface irrigation, the soil series coded 13, 16, 17, 18 and 20 (4233.46 ha – 11.36%) were highly suitable (S_1); soil series coded 1, 12, 15, 19, 21 and 22 (14041.96 ha – 37.62 %) were classified as moderately suitable (S_2), soil series coded 3, 4, 5 and 9 (8835.99 ha – 23.66%) were found to be marginally suitable (S_3). soil series coded 6 and 14 (1033.86 ha – 2.77%) were classified as currently not-suitable (N_1) and soil series coded 2, 7, 8, 10 and 11 (8714.66 ha – 23.34 %) were classified as permanently not-suitable (N_2) for any surface irrigation practices.

The analysis of the suitability irrigation maps for surface irrigation (Fig. 2) indicate that some portion of the cultivated area in this plain (located in the east) is deemed as being highly suitable land due to deep soil, good drainage, texture, salinity and proper slope of the area. The moderately suitable area is mainly located to the center, and east of this area due to soil texture and drainage limitations. Other factors such as depth and slope have no influence on the suitability of the area whatsoever. The map also indicates that some part of the cultivated area in this plain was evaluated as marginally suitable because of the

Codes of Land Units	Surface Irrigation		Sprinkle Irrigation		Drip Irrigation	
	Ci	suitability classes	Ci	suitability classes	Ci	suitability classes
1	70.2	S2 sw [a]	76.5	S2 sw [b]	72	S2 sw [c]
2	11.40	N2 snw	12.6	N2 snw	12.8	N2 snw
3	59.23	S3 sw	76.95	S2 s	76	S2 s
4	52.21	S3 sw	57.37	S3 sw	54.4	S3 sw
5	59.23	S3 sw	76.95	S2 s	76	S2 s
6	40.27	N1snw	47.23	S3 sw	45.22	S3 sw
7	17.90	N2 snw	22.37	N2 snw	22.1	N2 snw
8	20.88	N2 snw	25.81	N2 snw	25.5	N2 snw
9	52.65	S3 sw	58.5	S3 sw	56	S3 sw
10	20.88	N2 snw	25.81	N2 snw	25.5	N2 snw
11	17.90	N2 snw	22.37	N2 snw	22.1	N2 snw
12	71.07	S2 sw	76.95	S2 s	72	S2 S
13	87.75	S1	90	S1	80	S1
14	41.76	N1snw	48.76	S3 snw	46.24	S3 snw
15	78	S2 s	80	S1	70	S2 S
16	87.75	S1	90	S1	80	S1
17	83.36	S1	85.5	S1	76	S2 S
18	83.36	S1	85.5	S1	76	S2 S
19	78	S2 S	80	S1	70	S2 S
20	87.75	S1	90	S1	80	S1
21	74.1	S2 s	76	S2 S	66.5	S2 S
22	78.97	S2 sn	85.5	S1	76	S2 S

a & b . Limiting Factors for Surface and Sprinkle Irrigations: n: (Salinity & Alkalinity), w: (Drainage) and s: (Soil Texture).
c. Limiting Factors for Drip Irrigation: s: (Calcium Carbonate & Soil Texture), w: (Drainage) and n: (Salinity & Alkalinity).

Table 4. Ci Values and Suitability Classes of Surface ,Sprinkle and Drip irrigation for Each Land Units.

drainage and soil texture limitations. The current non-suitable land and permanently non-suitable land can be observed only in the west and center of the plain because of very severe limitation of salinity & alkalinity, drainage and soil texture. For almost the total study area elements such as soil depth, slope and $CaCO_3$ were not considered as limiting factors.

In order to verify the possible effects of different management practices, the land suitability for sprinkle and drip irrigation was evaluated (Tables 4 and 5).

For sprinkle irrigation, soil series coded 13, 15, 16, 17, 18, 19, 20 and 22 (9329.14 ha – 25.01%) were highly suitable (S_1) while soil series coded 1, 3, 5, 12 and 21 (14938.7 ha- 40.02%) were classified as moderately suitable (S_2). Further, soil series coded 4, 6, 9 and 14 (3877.43 ha – 10.38%) were found to be marginally suitable (S_3) and soil series coded 2, 7, 8, 10 and 11 (8714.66 ha – 23.34 %) were classified as permanently not-suitable (N_2) for sprinkle irrigation.

Suitability	Surface Irrigation			Sprinkle Irrigation			Drip Irrigation		
	Land unit	Area (ha)	Ratio (%)	Land unit	Area (ha)	Ratio (%)	Land unit	Area (ha)	Ratio (%)
S1	13 , 16 , 17 , 18 , 20	4233.46	11.36	13 , 15 , 16 , 17 , 18 , 19 , 20 , 22	9329.14	25.01	13 , 16 , 20	1724.88	4.64
S2	1 , 12 , 15 , 19 , 21 , 22	14041.96	37.62	1 , 3 , 5 , 12 , 21	14938.7	40.02	1 , 3 , 5 , 12 , 15 , 17 , 18 , 19 , 21 , 22	22542.96	60.39
S3	3 , 4 , 5 , 9	8835.99	23.66	4 , 6 , 9 , 14	3877.43	10.38	4 , 6 , 9 , 14	3877.43	10.38
N1	6 , 14	1033.86	2.77	-	-	-	-	-	-
N2	2 , 7 , 8 , 10 , 11	8714.66	23.34	2 , 7 , 8 , 10, 11	8714.66	23.34	2 , 7 , 8 , 10 , 11	8714.66	23.34
[a]Mis Land		464.99	1.25		464.99	1.25		464.99	1.25
Total		37324.91	100		37324.91	100		37324.91	100

a. Miscellaneous Land: (Hill, Sand Dune and River Bed)

Table 5. Distribution of Surface, Sprinkle and Drip Irrigation Suitability.

Regarding sprinkler irrigation, (Fig. 3) the highly suitable area can be observed in the some part of the cultivated zone in this plain (located in the east) due to deep soil, good drainage, texture, salinity and proper slope of the area. As seen from the map, the largest part of the cultivated area in this plain was evaluated as moderately suitable for sprinkle irrigation because of the moderate limitations of drainage and soil texture. Other factors such as depth, salinity and slope never influence the suitability of the area. The marginally suitable lands are located only in the North and south of the plain. The permanently non-suitable land can be observed in the west and center of the plain and their non-suitability of the land are due to the severe limitations of salinity & alkalinity, drainage and soil texture. The current non-suitable lands did not exist in this plain. For almost the entire study area slope, soil depth and $CaCO_3$ were never taken as limiting factors.

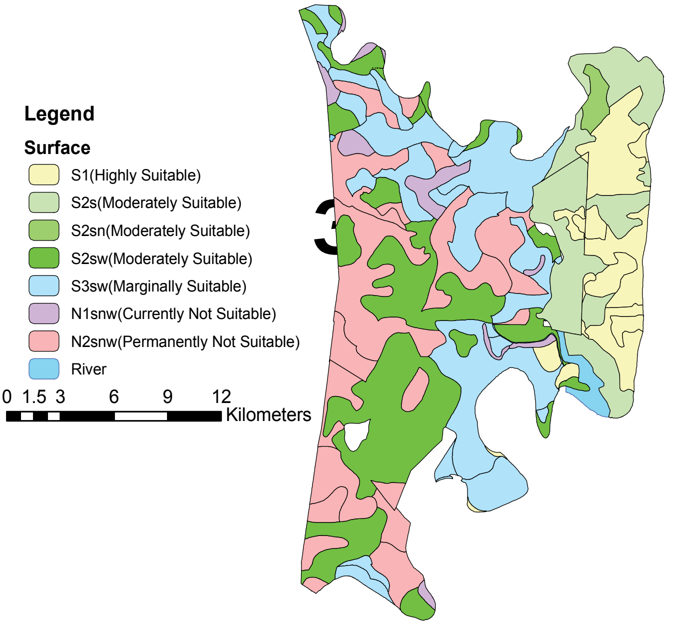


Fig. 2. Land Suitability Map for Surface Irrigation.

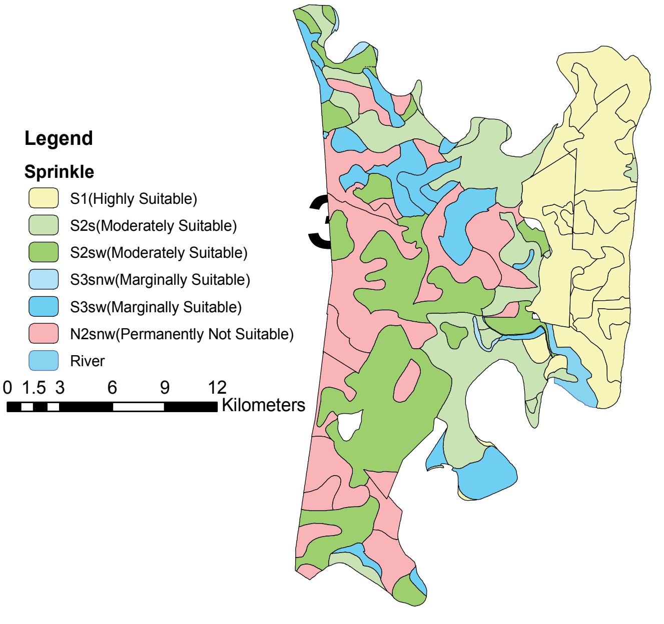


Fig. 3. Land Suitability Map for Sprinkle Irrigation.

For drip irrigation, soil series coded 13, 16 and 20 (1724.88 ha-4.64%) were highly suitable (S_1) while soil series coded 1, 3, 5, 12, 15, 17, 18, 19, 21 and 22 (22542.96 ha- 60.39%) were classified as moderately suitable (S_2). Further, soil series coded 4, 6, 9 and 14 (3877.43 ha, 10.38%) were found to be slightly suitable (S_3) and soil series coded 2, 7, 8, 10 and 11 (8714.66 ha – 23.34 %) were classified as permanently not-suitable (N_2) for drip irrigation.

Regarding drip irrigation, (Fig. 4) the highly suitable lands covered the smallest part of the plain. The slope, soil texture, soil depth, calcium carbonate, salinity and drainage were in good conditions .The moderately suitable lands could be observed over a large portion of the plain (east, north and south parts) due to the medium content of calcium carbonate. The marginally suitable lands were found only in the Northwest and southeast of the area .The limiting factors for this land unit were drainage and the medium content of calcium carbonate. The permanently non-suitable land can be observed in the west and center of the plain and their non-suitability of the land are due to the severe limitations of calcium carbonate, salinity & alkalinity, drainage and soil texture. The current non-suitable lands did not exist in this plain. For almost the entire study area slope, soil depths were never taken as limiting factors.

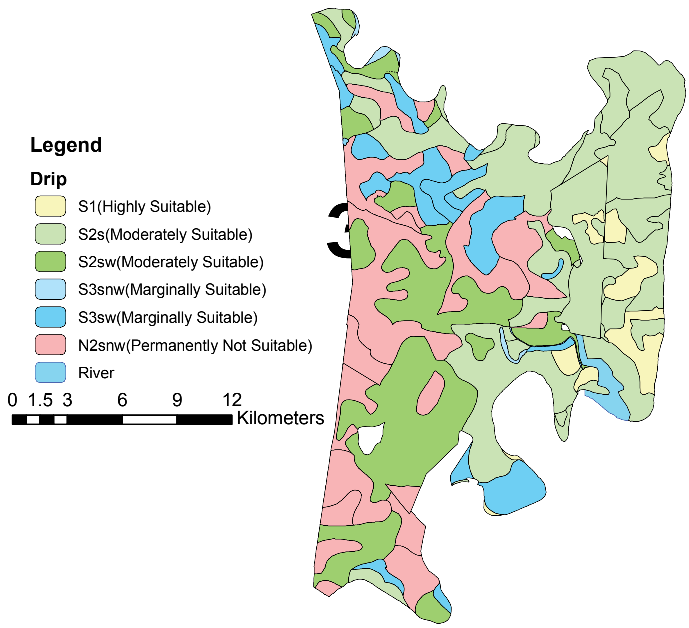


Fig. 4. Land Suitability Map for Drip Irrigation.

The mean capability index (Ci) for surface irrigation was 55.90 (Marginally suitable) while for sprinkle irrigation it was 62.33 (Moderately suitable). Moreover, for drip irrigation it was 58.31 (Marginally suitable). For the comparison of the capability indices for surface, sprinkle and drip irrigation. Tables 6 indicated that in soil series coded 2 applying drip irrigation systems was the most suitable option as compared to surface and sprinkle irrigation systems. In soil series coded 1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21 and 22 applying sprinkle irrigation systems was more suitable then surface and drip irrigation systems. Fig.5 shows the most suitable map for surface, sprinkle and drip irrigation systems in the West north ahwaz plain as per the capability index (Ci) for different irrigation systems. As seen from this map, the largest part of this plain was suitable for sprinkle irrigation systems and some parts of this area was suitable for drip irrigation systems.

The results of Tables 4, 5 and 6indicated that by applying sprinkle irrigation instead of surface and drip irrigation methods, the land suitability of 35038,81 ha (93.87%) of the west north ahwaz Plain's land could be improved substantially. However by applying drip Irrigation instead of surface and sprinkle irrigation methods, the suitability of 1821,12 ha (4.88%) of this Plain's land could be improved. The comparison of the different types of irrigation revealed that sprinkle irrigation was more effective and efficient then the drip and surface irrigation methods and improved land suitability for irrigation purposes. The second best option was the application of drip irrigation which was considered as being more practical than the surface irrigation method. To sum up the most suitable irrigation systems for the west north ahwaz Plain' were sprinkle irrigation, drip irrigation and surface irrigation respectively. Moreover, the main limiting factor in using surface and sprinkle irrigation methods in this area were salinity & alkalinity, drainage and soil texture and the main limiting factors in using drip irrigation methods were the salinity & alkalinity, drainage, soil texture and calcium carbonate.

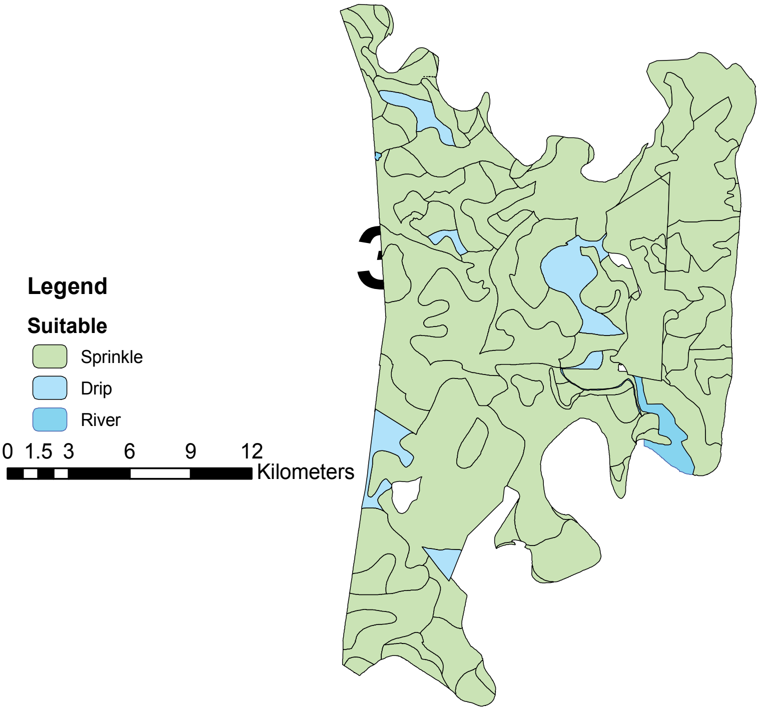


Fig. 5. The most suitable map for different irrigation systems.

Codes of Land Units	The Maximum Capability Index for Irrigation(Ci)	Suitability Classes	The Most Suitable Irrigation Systems	Limiting Factors
1	76.5	S2 sw	Sprinkle	Soil Texture and Drainage
2	12.8	N2 snw	Drip	CaCo3& Soil Texture, Salinity & Alkalinity and Drainage
3	76.95	S2 s	Sprinkle	Soil Texture
4	57.37	S3 sw	Sprinkle	Soil Texture and Drainage
5	76.95	S2 s	Sprinkle	Soil Texture
6	47.23	S3 sw	Sprinkle	Soil Texture and Drainage
7	22.37	N2 snw	Sprinkle	Soil Texture , Salinity & Alkalinity and Drainage
8	25.81	N2 snw	Sprinkle	Soil Texture , Salinity & Alkalinity and Drainage
9	58.5	S3 sw	Sprinkle	Soil Texture and Drainage
10	25.81	N2 snw	Sprinkle	Soil Texture , Salinity & Alkalinity and Drainage
11	22.37	N2 snw	Sprinkle	Soil Texture , Salinity & Alkalinity and Drainage
12	76.95	S2 s	Sprinkle	Soil Texture
13	90	S1	Sprinkle	No Exist
14	48.76	S3 snw	Sprinkle	Soil Texture , Salinity & Alkalinity and Drainage
15	80	S1	Sprinkle	No Exist
16	90	S1	Sprinkle	No Exist
17	85.5	S1	Sprinkle	No Exist
18	85.5	S1	Sprinkle	No Exist
19	80	S1	Sprinkle	No Exist
20	90	S1	Sprinkle	No Exist
21	76	S2s	Sprinkle	Soil Texture
22	85.5	S1	Sprinkle	No Exist

Table 6. The Most Suitable Land Units for Surface, Sprinkle and Drip Irrigation Systems by Notation to Capability Index (Ci) for Different Irrigation Systems.

4. Conclusions

Several parameters were used for the analysis of the field data in order to compare the suitability of different irrigation systems. The analyzed parameters included soil and land characteristics. The results obtained showed that sprinkle and drip irrigation systems are more suitable than surface irrigation method for most of the study area. The major limiting factor for both sprinkle and surface irrigation methods were salinity & alkalinity, drainage and soil texture. However for drip irrigation method, salinity & alkalinity, drainage, soil texture and calcium carbonate were restricting factors. The results of the comparison between the maps indicated that the introduction of a different irrigation management policy would provide an optimal solution in as such that the application of sprinkle and drip irrigation techniques could provide beneficial and advantageous. This is the current strategy adopted by large companies cultivating in the area and it will provide to be economically viable for Farmers in the long run.Such a change in irrigation management practices would imply the availability of larger initial capitals to farmers (different credit conditions, for example) as well as a different storage and market organization. On the other hand, because of the insufficiency of water in arid and semi arid climate, the optimization of water use efficiency is necessary to produce more crops per drop and to help resolve water shortage problems in the local agricultural sector. The shift from surface irrigation to high-tech irrigation technologies, e.g. sprinkle and drip irrigation systems, therefore, offers significant water-saving potentials. On the other hand, since sprinkle and drip irrigation systems typically apply lesser amounts of water (as compared with surface irrigations methods) on a frequent basis to maintain soil water near field capacity, it would be more beneficial to use sprinkle and drip irrigations methods in this plain.

In this study, an attempt has been made to analyze and compare three irrigation systems by taking into account various soil and land characteristics. The results obtained showed that sprinkle and drip irrigation methods are more suitable than surface or gravity irrigation method for most of the soils tested. Moreover, because of the insufficiency of surface and ground water resources, and the aridity and semi-aridity of the climate in this area, sprinkle and drip irrigation methods are highly recommended for a sustainable use of this natural resource; hence, the changing of current irrigation methods from gravity (surface) to pressurized (sprinkle and drip) in the study area are proposed.

5. Acknowledgements

The writers gratefully acknowledge the Research and Standards Office for Irrigation and Drainage Networks of Khuzestan Water and Power Authority (KWPA) and Shahid Chamran University for their financial support and assistance during the study and field visits.

6. References

Albaji, M. Landi, A. Boroomand Nasab, S. & Moravej, K.(2007). Land Suitability Evaluation for Surface and Drip Irrigation in Shavoor Plain Iran *Journal of Applied Sciences,* 8(4):654-659.

Albaji, M. Boroomand Nasab, S. Kashkoli, H.A. & Naseri, A.A. (2010a). Comparison of different irrigation methods based on the parametric evaluation approach in the plain west of Shush, Iran. *Irrig. & Drain*. ICID.

Albaji, M. Boroomand Nasab, S. Naseri, A.A. & Jafari, S. (2010b). Comparison of different irrigation methods based on the parametric evaluation approach in Abbas plain—Iran. *J. Irrig. and Drain Eng. (ASCE)* 136 (2), 131–136.

Albaji, M. Shahnazari,A. Behzad,M. Naseri, A.A. Boroomand Nasab, S. & Golabi,M.(2010c). Comparison of different irrigation methods based on the parametric evaluation approach in Dosalegh plain: Iran. *Agricultural Water Management* 97 (2010) 1093–1098.

Albaji, M. & Hemadi, J. (2011). Investigation of different irrigation systems based on the parametric evaluation approach on the Dasht Bozorg Plain. *Transactions of the Royal Society of South Africa*. Vol. 66(3), October 2011.DOI: 10.1080/0035919X.2011.622809. http://www.informaworld.com.

Barberis, A. & Minelli, S. (2005). *Land Evaluation in the Shouyang County, Shanxi Province, China.* 25th Course Professional Master. 8th Nov 2004-23 Jun 2005.IAO,Florence,Italy. < http://www.iao.florence.it/training/geomatics/Shouyang/China_25hq.pdf>.

Bazzani, F. & Incerti, F. (2002). *Land Evaluation in the Province of Larache,Morocco*. 22nd Course Professional Master. Geometric and Natural Resources Evaluation. 12 Nov 2001-21 June 2002. IAO, Florence, Italy. < http:// www.iao.florence.it/training/geomatics/Larache/Morocco_22.pdf>.

Bienvenue, J .S. Ngardeta, M. & Mamadou, K. (2003). *Land Evaluation in the Province of Thies, Senegal* . 23rd Course Professional Master. Geometric and Natural Resources Evaluation.8th Nov 2002-20 June 2003. IAO, Florence,Italy. <http://www.iao.florence.it/training/geomatics/Thies/senegal23.pdf>.

Briza, Y. Dileonardo, F. & Spisni, A. (2001). *Land Evaluation in the Province of Ben Slimane, Morocco.* 21 st Course Professional Master.Remote Sensing and Natural Resource Evaluation .10 Nov 2000 - 22 June 2001. IAO, Florence, Italy. <http://www.iao.florence.it/training/geomatics/BenSlimane/Marocco21.pdf>.

Dengize, O. (2006). A Comparison of Different Irrigation Methods Based on the Parametric Evaluation Approach. *Turk. J. Agric For*, 30: 21 – 29. http://journals.tubitak.gov.tr/agriculture/issues/tar-06-30-1/tar-30-1-3-0505-15.pdf.

Food and Agriculture Organization of the United Nations (FAO). (1976). A Framework for Land Evaluation. *Soil Bulletin No.32*. FAO,Rome,Italy.72 pp. < http:// www.fao.org/docrep/x5310e/x5310e00.htm>.

Hargreaves, H.G. & Mekley, G.P. (1998). *Irrigation fundamentals*. Water Resource Publication, LLC. 200 Pp.

Keys to soil taxonomy. (2008). U.S, Department of Agriculture. By Soil Survey Staff. Washington, DC, USA.< http://www.statlab.iastate.edu/soils/keytax>.

Khuzestan Water and Power Authority (KWPA). (2005*). Meteorology Report of West north ahwaz Plain, Iran* (in Persian)."< http://www.kwpa.com>.

Khuzestan Water and Power Authority (KWPA). (2009). *Semi-detailed Soil Study Report of West north ahwaz Plain, Iran* (in Persian). <http://www.kwpa.com>.

Liu, W., Qin, Y. & Vital, L. (2006). *Land Evaluation in Danling county ,Sichuan province, China.* 26th Course Professional Master. Geometric and Natural Resources Evaluation. 7th Nov 2005–23rd Jun 2006. IAO, Florence, Italy. < http://www.iao.florence.it/training/geomatics/Danling/China_26.pdf>.

Mbodj ,C. Mahjoub, I. & Sghaiev, N.(2004). *Land Evaluation in the Oud Rmel Catchment, Tunisia.* 24th Course Professional Master. Geometric and Natural Resources Evaluation. 10th Nov 2003–23 rd Jun 2004. IAO, Florence, Italy. <http:// www.iao.florence.it/training/geomatics/Zaghouan/Tunisia_24lq.pdf>.

Sys, C. Van Ranst, E . & Debaveye, J. (1991). *Land Evaluation, Part l, Principles in Land Evaluation and Crop Production Calculations.* International Training Centre for Post-graduate Soil Scientists, University Ghent. < http://www.plr.ugent.be/publicatie.html>.

Part 3

Sustainable Irrigation Development and Management

14

Guideline for Groundwater Resource Management Using the GIS Tools in Arid to Semi Arid Climate Regions

Salwa Saidi[1], Salem Bouri[1], Brice Anselme[2] and Hamed Ben Dhia[1]
[1]*Water, Energy and Environment Laboratory (LR3E), ENIS, Sfax*
[2]*PRODIG Laboratory, Sorbonne University, Paris*
[1]*Tunisia*
[2]*France*

1. Introduction

The quality of groundwater is generally under a considerable potential of contamination especially in coastal areas with arid and semi-arid climate like the study area. It is also characterized by intensive agriculture activities, improper disposal of wastewater, and occurrence of olive mills. In addition the intensity of exploitation, often characterized by irrational use, imposes pressures on groundwater reserves. Therefore, there is clearly an urgent need for rapid reconnaissance techniques that allow a protection of groundwater resources of this area.

Groundwater management and protection constitutes an expensive undertaking because of the prohibitive costs and time requirements. To preserve the groundwater resources a simple susceptibility indexing method, based on vulnerability and quality index, was proposed.

The groundwater vulnerability assessment has recently become an increasingly important environment management tool for local governments. It allows for better understanding of the vulnerabilities associated with the pollution of local groundwater sub areas, according to local hydrological, geological or meteorological conditions. The adopted method was specifically developed for groundwater vulnerability DRASTIC method and it is a widely used in many cases of study (Aller et al., 1987; Saidi et al., 2009 and 2011;Rahman, 2008). The DRASTIC model is based on seven parameters, corresponding to the seven layers to be used as input parameters for modeling, including depth to water table (D), recharge (R), aquifer type (A), soil type (S), topography (T), impact of vadose zone (I) and conductivity (C). Vulnerability index is defined as a weighted sum of ratings of these parameters. The quality index calculation procedure, based on the water classification, was introduced to evaluate hydrochemical data.

Therefore the main objective of this study is to propose some water management scenarios by performing the susceptibility index (Pusatli et al., 2009) for drinking and irrigation water. The first objective was to evaluate the susceptibility index. To this end, a combination of both vulnerability and water quality maps has been considered. The second objective was to classify the study area into zones according to each degree of susceptibility and some alternatives to manage the groundwater resources of the Chebba – Mellouleche aquifer were proposed.

A geographic information system (GIS) offers the tools to manage, manipulate process, analyze, map, and spatially organize the data to facilitate the vulnerability analysis. In addition, GIS is a sound approach to evaluate the outcomes of various management alternatives are designed to collect diverse spatial data to represent spatially variable phenomena by applying a series of overlay analysis of data layers that are in spatial register.

2. Study area

The region, object of this study, is the Chebba – Mellouleche aquifer which is situated in the Eastern Tunisia with a total surface of 510 km^2 and a coastline of 51Km (Fig. 1). This region is characterized by a semi-arid climate, with large temperature and rainfall variations. Averages of annual temperature and rainfall are about 19.8°C and 225 mm, respectively (Anon., 2007a). It is known for intensive anthropogenic activities such as industrial and especially agricultural ones which is concentrated in its North east part (Fig. 1).

Both of the aquifer and the vadose zone of the Chebba– Mellouleche region are located in Plio-Quaternary layer system which is constituted mainly by alluvial fan, gravel, sand, silt and clay with high permeability (Saidi et al., 2009). Hence, it results in an easily infiltration of nutrients in the groundwater. The aquifer has an estimated safe yield of 3.24 10^6 m^3/yr, but annual abstraction by pumping from 4643 wells stands at 4.28 10^6 m^3/yr (CRDA, 2005).

The groundwater supply is under threat due to salinisation as salinity measures are generally of 1.5–3 g/l in the majority of the coastal Aquifer, and exceed 6 g/L in the West (Anon., 2007b). For these reasons, a new water management planning is highly required.

3. Methodology

It is noted that an integration of hydrogeological and hydrochemical parameters through the use of the susceptibility index method should be considered as a reliable tool for groundwater quality protection and decision making in this region.

To reach this aim, a variety of GIS analysis and geo - processing framework, which includes: Arc Map, Arc Catalog, Arc Scene and Model Builder of the Arc GIS 9.2 were used (Rahman, 2008).

3.1 Susceptibility index (S_I)

The contamination susceptibility index (S_I) was calculated by considering the product of the vulnerability index (V_I) and the quality index (Q_I) using the following equation (Pusatli et al., 2009):

$$S_I = V_I * Q_I \quad (1)$$

3.1.1 Vulnerability index (V_I)

In the present study the DRASTIC method, a standard system for evaluating groundwater pollution potential is used. The DRASTIC model is very used all over the world because the input information required for its application is either readily available or easily

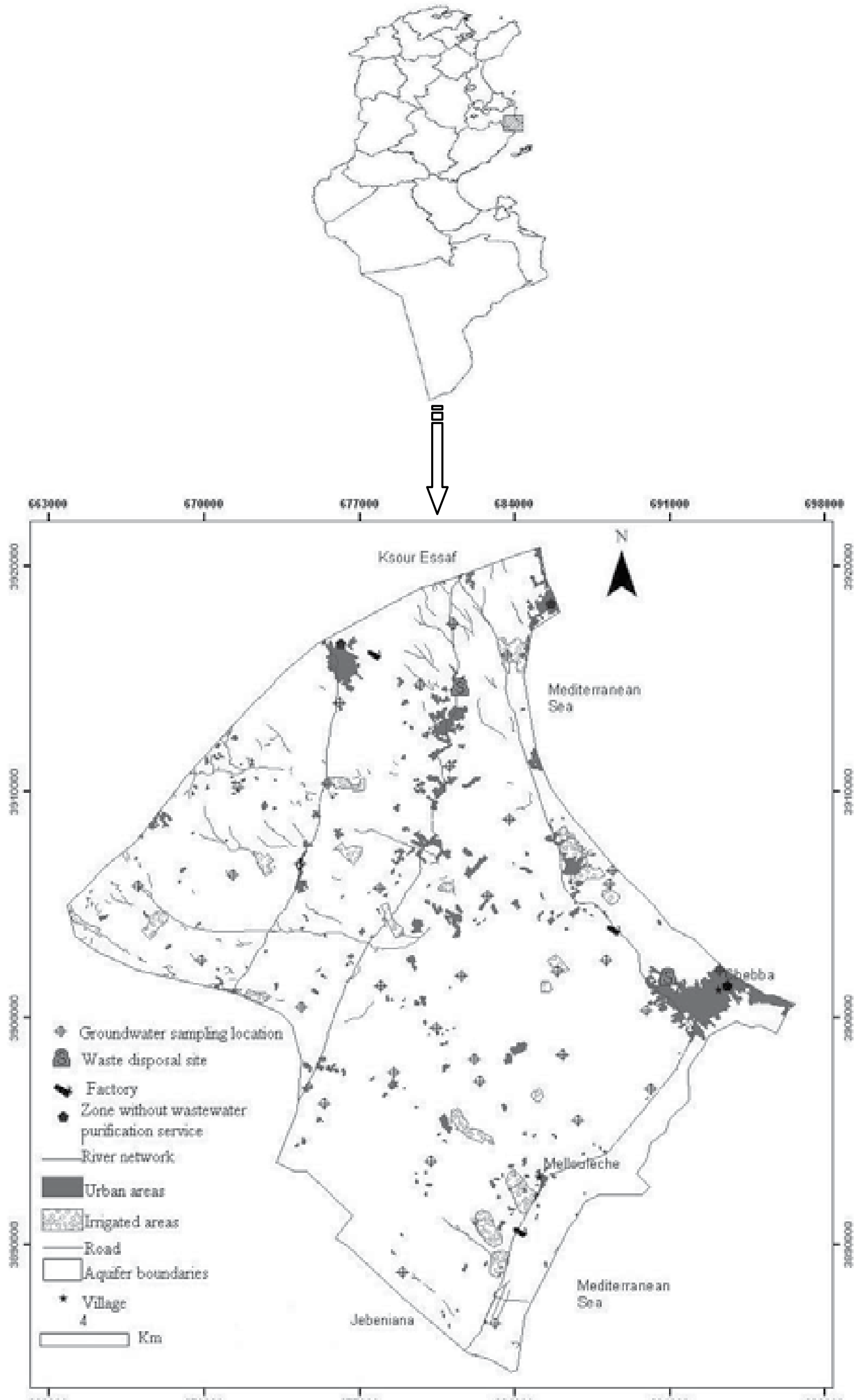


Fig. 1. Location of the study area.

obtained from various government agencies. This model was developed for the purpose of groundwater protection in the United States of America and its methodology is referred as ''DRASTIC.'' This methodology developed as a result of a cooperative agreement between the NWWA and the US Environmental Protection Agency (EPA). It was designed to provide systematic evaluation of GW pollution potential based on seven parameters whose required information were obtained from various Government and semi-Government agencies at a desired scale (Table 1). The acronym DRASTIC stands for the seven hydrogeologic parameters used in the model which are: Depth of water, Net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and hydraulic Conductivity:

Parameter	Data and Sources	Mode of processing
Vulnerability (V_I) or DRASTIC Parameters		
D	Monthly monitoring of shallow wells in 2007 (Anon., 2007b).	Interpolation
R	Precipitation, Evapotranspiration (Anon., 2007a).	Interpolation
A	Geological information (Bedir, 1995), well logs (Anon., 2007).	Interpolation
S	Soil maps (scale 1:50,000) (Anon., 2008).	Digitalization
T	Topographical maps (scale 1:50000) (Anon., 2008).	Digitalization
I	Analysis of water logs and geological maps (Anon., 2007b).	Interpolation
C	Pumping tests (Anon., 2007c).	Interpolation
Quality index (Q_I)	Chemical composition of water wells samples (Anon., 2007c and Trabelsi, 2008)	Interpolation

Table 1. Data sources of susceptibility index (VI and QI) parameters

Depth to groundwater (D): It represents one of the most important factors because it determines the thickness of the material through which infiltrating water must travel before reaching the aquifer-saturated zone. In general, the aquifer potential protection increases with its water depth. The borewell and borehole data was collected from Mahdia Agricultural Agency.

Net Recharge (R): The net recharge is the amount of water from precipitation and artificial sources available to migrate down to the groundwater. Recharge water is, therefore, a significant vehicle for percolating and transporting contaminants within the vadose zone to the saturated zone. To calculate the distribution of the recharge parameter, the water table fluctuations (WTF) method was used. This method estimates groundwater recharge as the product of specific yield and the annual rate of water table rate including the total groundwater draft (Sophocleous, 1991).

Aquifer media (A) and the impact of the vadose zone (I): were represented by the lithology of the saturated and unsaturated zones, which is found in well logs (Saidi et al., 2009).

Topography (T): was represented by the slopes map (1/50 000 scale) covering the study area.

Soil media (S): It considers the uppermost part of the vadose zone and it influences the pollution potential. A soil map, for the study area, was obtained by digitizing the existing soil maps covering the region (Anon., 2008).

Hydraulic conductivity (C): It refers to the ability of the aquifer materials to transmit water, which in turn, controls the rate at which ground water will flow under a given hydraulic gradient. The rate at which the ground water flows also controls the rate at which a contaminant moves away from the point at which it enters the aquifer (Aller et al., 1987).

The hydraulic Conductivity was calculated based on the following equation

$$K = T/b, \quad (2)$$

where K is the hydraulic conductivity of the aquifer (m/s), b is the thickness of the aquifer (m) and T is the transmissivity (m^2/s), measured from the field pumping tests data.

It is divided into ranges where high values are associated with higher pollution potential. Figure 2 shows the relative importance of the ranges.

Thus, thematic maps representing the D, R, A, I and C parameters were created by interpolation of data used for each one (Table 1). However, the soil type and topography maps are geo-referenced and digitized from different data files (Saidi et al., 2009).

The final vulnerability index is computed as the weighted sum overlay of the seven layers using the following equation:

$$V_I = Dr\, Dw + Rr\, Rw + Ar\, Aw + Sr\, Sw + Tr\, Tw + Ir\, Iw + Cr\, Cw \quad (3)$$

where D, R, A, S, T, I, and C are the seven parameters and the subscripts r and w are the corresponding rating and weights, respectively.

The DRASTIC vulnerability index was determined from multidisciplinary studies as shown in Table 1. The distributed value of each parameter was the rated in each cell of the grid map of 300 m by 300 m cell dimensions. According to the range of Aller et al. (1987), the contamination vulnerability index was created by overlying the seven thematic layers using intersect function of analysis tools in the Arc Map.

3.1.2 Modification of the weights of the DRASTIC method

The “real” weight is a function of the other six parameters as well as the weight assigned to it by the DRASTIC model (Saidi et al., 2011).

In this analysis real or ‘‘effective’’ weight of each parameter was compared with its assigned or ‘‘theoretical’’ weight. The effective weight of a parameter in a sub-area was calculated by using the following equation:

$$W = ((P_r\, P_w)/V_I)*100 \quad (4)$$

where W refers to the “effective” weight of each parameter, P_r and P_w are the rating value and weight for each parameter and V_I is the overall vulnerability index.

3.1.3 Quality index (Q_I)

The quality index calculation is based on the quality classes of ions, which were determined using the concentrations of ions in groundwater at a given location. In this application, we used four classification schemes that are described in the following references: WCCR (1991), Anon. (2003), Neubert and Benabdallah (2003) and WHO (2006). In this classification, the irrigation water quality is classified into five groups with respect to each ion concentration as very good (I), good (II), usable (III), usable with caution (IV) and harmful (V). The classification limits used in this study for the considered parameters are listed in Table 2.

1- Irrigation water classification

Parameters	Irrigation water limits				
	Class I (very good)	Class II (good)	Class III (usable)	Class IV (usable with caution)	Class V (harmful)
EC (µS/cm)	0 – 250	250 - 750	750 - 2000	2000 - 3000	> 3000
Cl (mg/l)	0 – 142	142 - 249	249 - 426	426 – 710	> 710
NO_3^- (mg/l)	0 – 10	10 - 30	30 - 50	50 – 100	> 100
SO_4^{2-} (mg/l)	0 – 192	192 - 336	336 - 575	576 – 960	> 960
Na^+ (mg/l)	0 – 69	69 - 200	200 - 252		> 252

2- Drinking water classification

Parameters	Irrigation water limits				
	Class I (very good)	Class II (good)	Class III (usable)	Class IV (usable with caution)	Class V (harmful)
EC (µS/cm)	0 – 180	180 - 400	400 - 2000	2000 – 3000	> 3000
Cl (mg/l)	0 - 25	25 - 200			> 200
NO_3^- (mg/l)	0 – 10	10 - 25	25 - 50		> 50
SO_4^{2-} (mg/l)	0 - 25	25 - 250			> 250
Na^+ (mg/l)	0 – 20	20 - 200			> 200

Table 2. Water classification (WCCR, 1991; Anonymous, 2003; Neubert et Benabdallah, 2003 and WHO, 2006)

The quality index at a given location can be calculated using the following formulation:

$$Q_I = P(Ci)^2 \tag{5}$$

where summation is overall considered quality parameters (ions). C is the determined class of parameter, i (ion), as an integer number (from 1 to 5) at a given location. The second power of C was used to enhance the effect of poor quality classes in the index (Saidi et al., 2009). In order to determine the chemical composition of the Chebba– Mellouleche groundwater during the irrigation period, 33 samples were collected from wells and analyzed in July 2007 (Saidi, 2011) (Fig. 1). Groundwater samples were taken from 27 wells of the Chebba – Mellouleche Aquifer.

3.2 Water management propositions

The builder model, describing the methodology applied to assess the water susceptibility index, was created using the Arc Tool Box in Arc Map interface of Arc GIS 9.2 (Saidi et al., 2009). Next, it is possible to propose a management plan by overlying the susceptibility index maps for irrigation and drinking water.

4. Results and discussions

4.1 Modification of the DRASTIC weights

The "real" or effective weights of the DRASTIC parameters exhibited some deviation from the "theoretical" weight (Table 3). The depth to groundwater table and the Aquifer media seem to be the most effective parameters in the vulnerability assessment; The depth of groundwater, D, with an average weight of 20.3% against a theoretical weight of 21.7% assigned by DRASTIC and the Aquifer media parameter, A (25.3%) against a theoretical weight of 13%. The net Recharge, R, the hydraulic conductivity, C, and especially the impact of the vadose zone, I, reveal lower "effective" weights when comparing with the "theoretical" weights.

Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (%)				Real weight after rescaling
			Mean	Minimum	Maximum	SD	
D	5	21.7	20,3	5	36	5,92	4.66
R	4	17.4	10,5	3	25	6,32	2,4
A	3	13	25,3	2	41	3.92	5,81
S	2	8.7	8	0	20	3.93	1,83
T	1	4.4	8.5	1	14	2,14	1.95
I	5	21.8	17	5	24	2,87	3,91
C	3	13	10,5	4	17	2,19	2,41

SD: standard deviation.

Table 3. Statistics of single parameter sensitivity analysis and a comparison between "theoretical" weight and "effective" weight.

4.2 Aquifer vulnerability

The vulnerability map shows three classes as indicated in Fig. 3. The highest class of vulnerability (140–159) covers 25% of the total surface. In fact, zones with high vulnerability correspond to the shallow groundwater table (<9 m), a flat topography (<5%), a high recharge and a permeable lithologies of the vadose zone and The Aquifer (made up of sand and gravel lithology). It results in a low capacity to attenuate the contaminants.

The areas with moderate to low vulnerability cover the rest of the study area, characterized by a deep groundwater table (> 25 m), low recharge (>150 mm) and lithology with low permeability (Table 4).

Using real weights, the high vulnerability class covers the whole of the southern part of the study area. It corresponds to the location of the irrigated areas, using intensive fertilizers. So, the utilization of the calculated or real weights can better reflect the pollution state of the study area than using theoretical weights, in groundwater vulnerability assessment. Therefore, the use of real weights in the DRASTIC index shows more similarity when comparing vulnerability degree and nitrate distribution (Figs. 3).

Fig. 2. Seven DRASTIC maps to compute the vulnerability index.

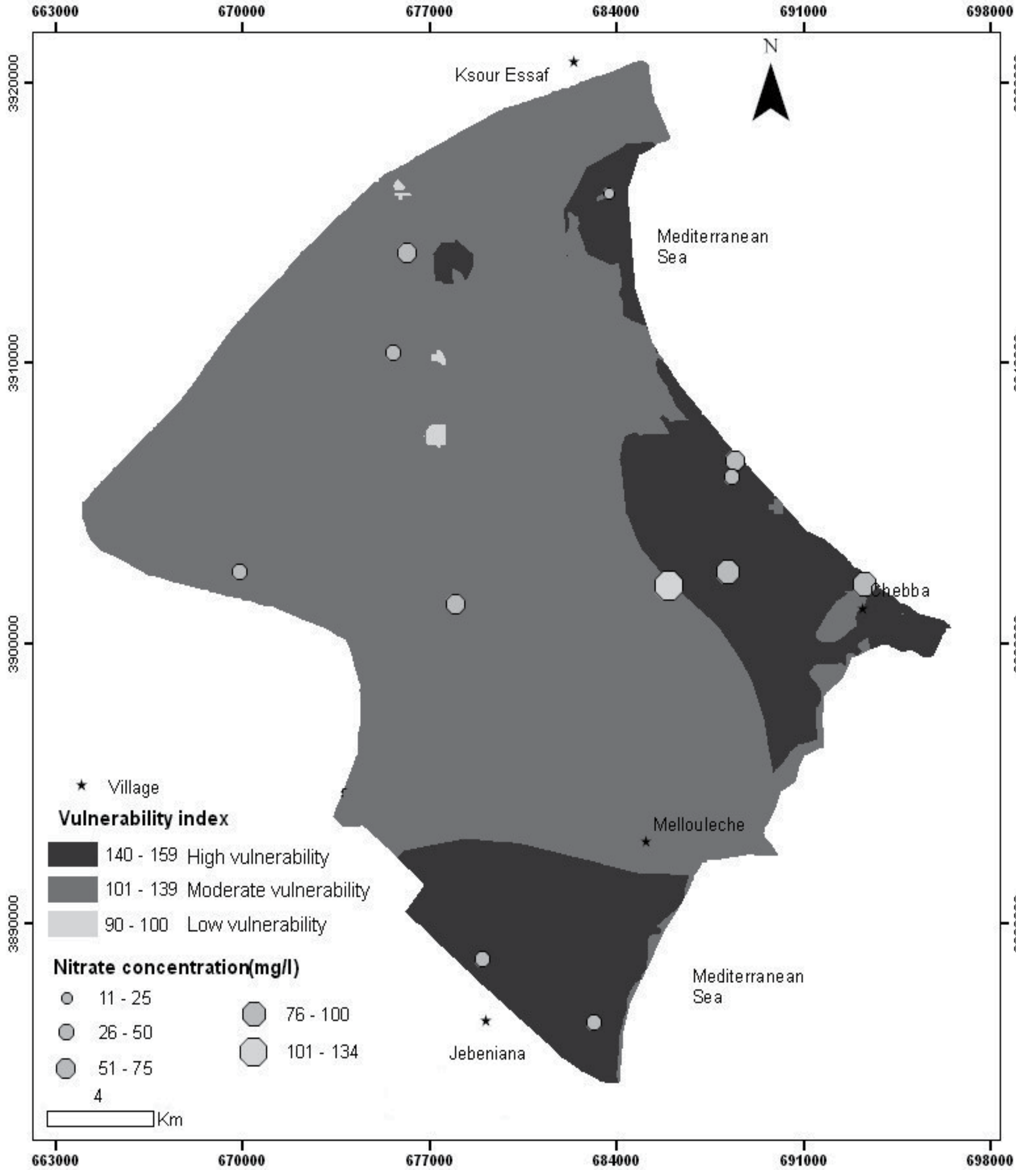


Fig. 3. Groundwater vulnerability and nitrate distribution in the Chebba – Mellouleche Aquifer using DRASTIC method (Saidi, 2011).

4.3 Water quality

Both the drinking and the irrigation water quality present a low quality, especially in the south of the Aquifer (Fig. 5). The main causes are the high permeability of its lithology as well as its localization in the vicinity of an irrigated area with intensive use of fertilizers. There is no similarity between vulnerability classes and water susceptibility classes. Thus, this proves the impact of the irrigation water quality on the aquifer groundwater quality.

Depth of water (m)		Net recharge (m)		Topography (slope) (%)		Hydraulic Conductivity (m/s)		Aquifer media		Impact of the vadose zone		Soil media	
Interval	R	Interval	R	Interval	R	Interval	R	Lithology classes	R	Lithology classes	R	Soil classes	
2-4.5	9	0.01–0.05	1	0-3%	10	$8.3*10^{-5}$ – $4*10^{-5}$	2	Sand and clay	1	confined Aquifer	1	Mineral soil	9
4.5–9	7	0.05–0.10	3	3–5%	9	$4*10^{-5}$ – $2.5*10^{-4}$	4	Massive clay and sand	2	Sandy clay and calcareous	2	Isohumic chestnut soil	8
9–15	5	0.10-0.18	6	5–10%	5	$2.5*10^{-4}$ – $4*10^{-4}$	6	Sand, gravel and clay	4	sand and silt	4	Rendzina	7
15-23	3	0.18-0.25	8	10-15%	3			Sandy gravel	8	Gravel and sand	10	Calcareous brown soil	6
23-32	2	>0.25	9					Gravel and Sand	10			Soil with little evolution	5
												Polygene-tic soil	4
												Gypsum soil	3
												Halomor-phic soil	2
												Urbain zones	1

R; Rank

Table 4. Ranks of the seven DRASTIC parameters (Aller et al., 1987).

For instance, the extreme North East part of the Aquifer has a high and a moderate vulnerability but a high water quality (low index). As a consequence, this area reveals a low water susceptibility index (Fig. 6). Nevertheless, the centre of the Aquifer which presented a low water quality and moderate vulnerability corresponds to a moderate water susceptibility index. This is due to the high permeability in this area which can cause a rapid infiltration of contaminant from the surface to the groundwater. But, in the South east a high vulnerability and a moderate to low water quality and the results are a moderate to low susceptibility index. The main reasons are probably the lithology of unsaturated zone and the comportment of the contaminants, in this area, which need further investigations (Saidi et al., 2009). The comparison between irrigation and drinking water maps show a few differences; the drinking water indexes are stricter than the irrigation ones (Fig. 6).

According to the drinking water susceptibility index map, people can exploit only the Northern part of the Aquifer for drinking uses and for irrigation of sensible plants. This is due to the high capacity of the unsaturated zone to attenuate the contaminant infiltration (made up of silt, clay and sandy clay) and the deep groundwater table in this area (>25 m) (Fig.2).

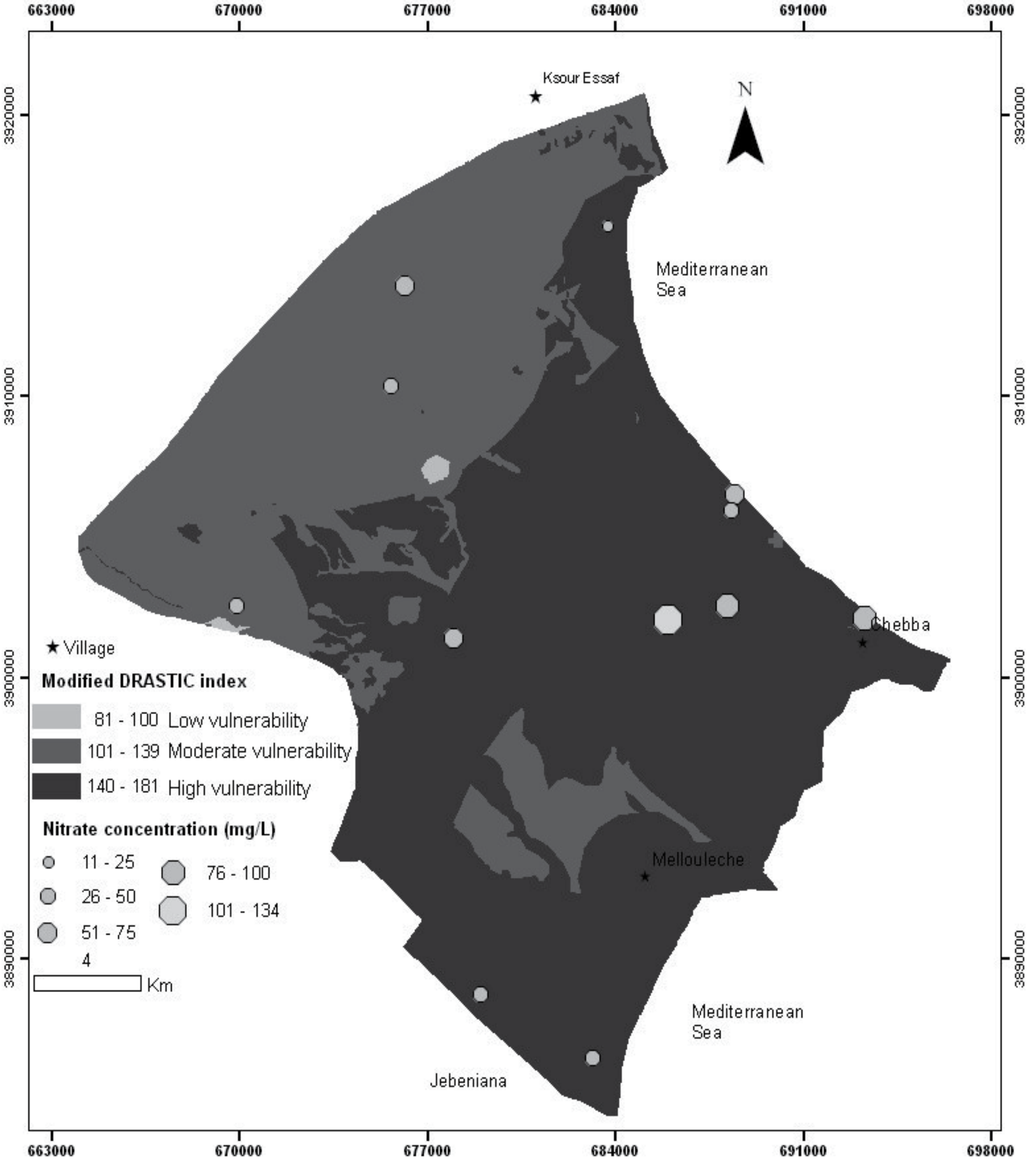


Fig. 4. Groundwater vulnerability and nitrate distribution in of the Chebba – Mellouleche Aquifer using modified DRASTIC method.

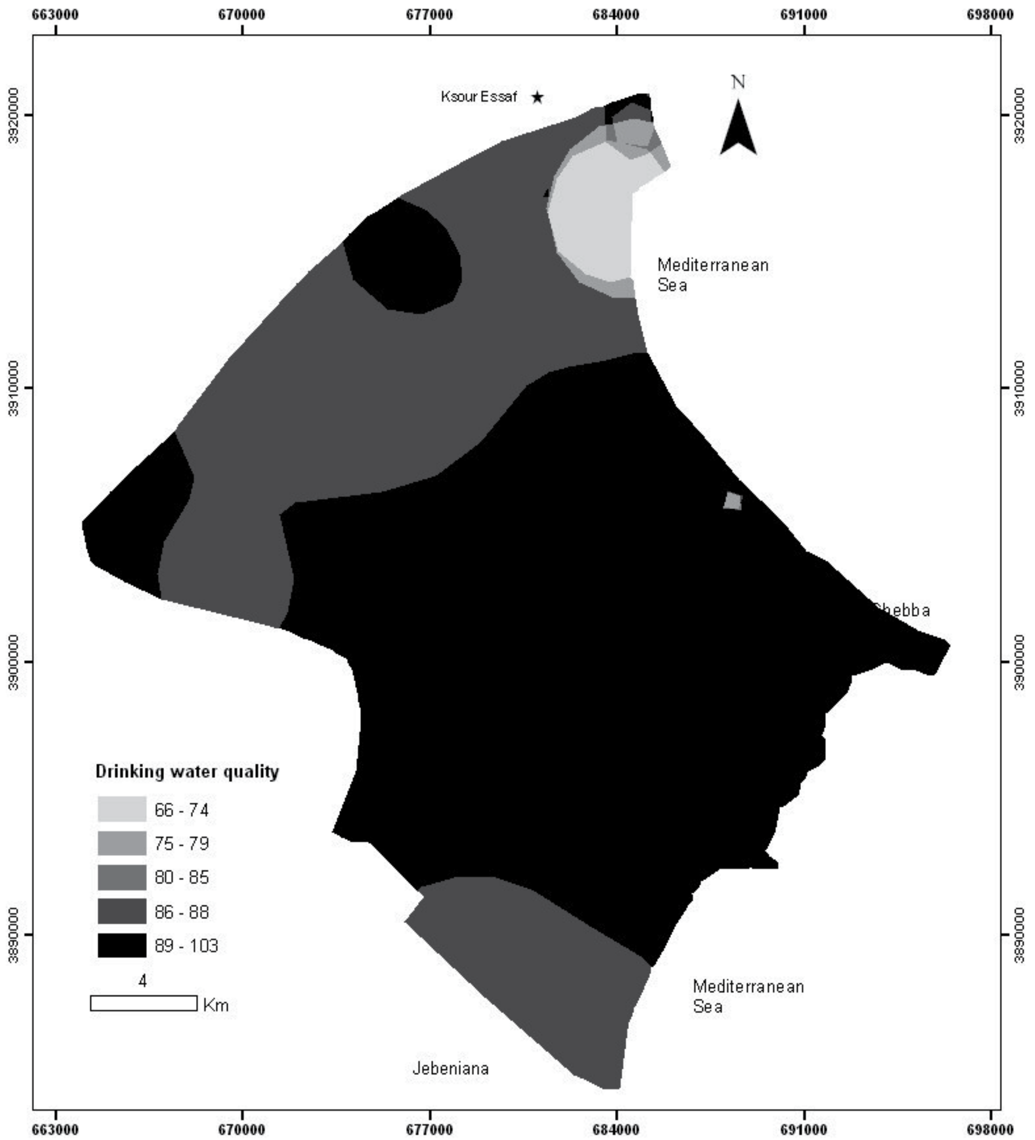


Fig. 5. Drinking water quality of the Chebba-Mellouleche Aquifer (Saidi et al., 2009).

However the Southern part of the study area presents a low water quality because it coincides with a variety of sites and activities which are hazardous to groundwater such as waste disposal sites (which have no technical or geological barrier), industrial estates (which have no proper sewage treatment facilities), agriculture (which applies fertilizers and pesticides abundantly) and fish farming in the vicinity of the coast (where antibiotic and pesticides are used in abundance and imports saltwater increases the salinity in the surrounding area) (Fig.6).

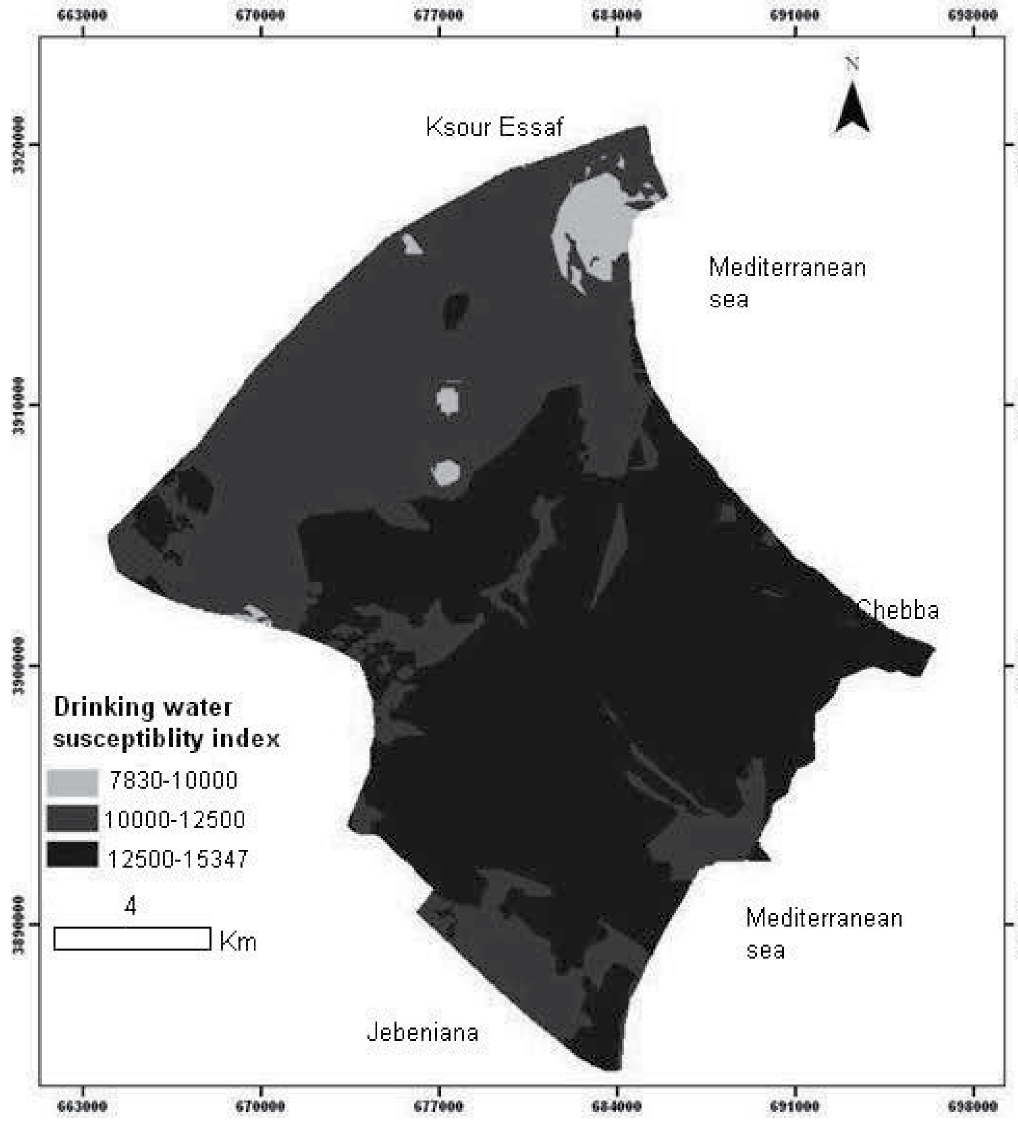


Fig. 6. Drinking water susceptibility index of the Chebba – Mellouleche Aquifer.

The Builder Model, created for the susceptibility indexing assessment, displays and provides a description of the procedures and the geo-processing operations which are used to create the susceptibility index maps (Fig. 7).

So, it can help to retain the main tools for the susceptibility assessment used in this study and facilitate the proposition of a water management schema (Saidi et al., 2009). In fact, a management map was created by overlaying the susceptibility index maps for irrigation and drinking water (Fig. 8).

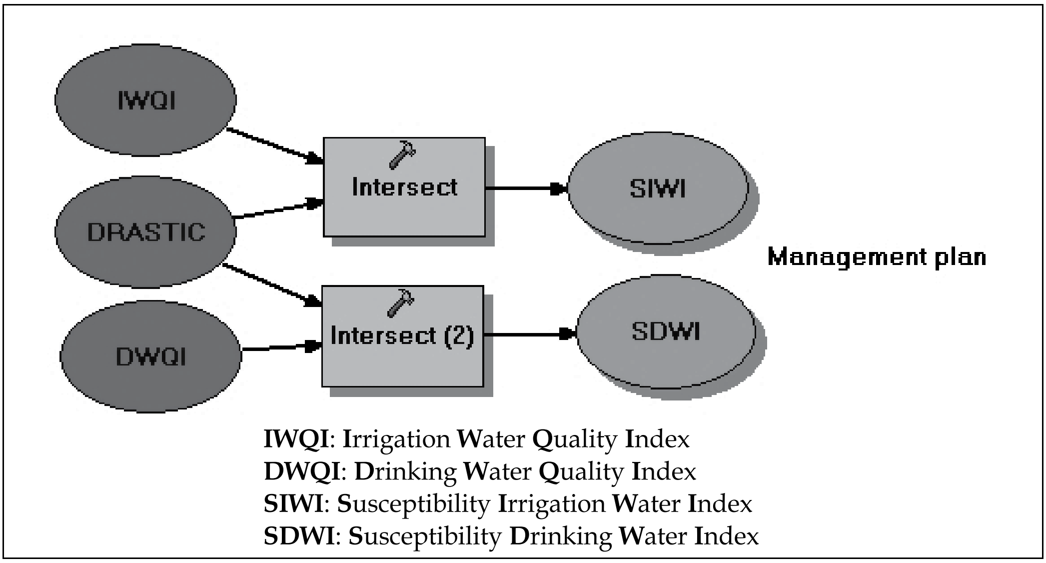


Fig. 7. Builder model for water management (Saidi et al., 2009).

This map shows that: (i) in the north of the aquifer the water can be used for drinking water and for irrigation of the sensible crops (ii) in the Extreme north eastern corner, the water has a high water quality but it represents a high risk since it is near to the coast. So, we should allow additional wells to ovoid seawater intrusion (iii) in the southern part of the study area, we should not allow additional high risk activities in order to obtain economic advantage and reduce environmental pollution hazard. Furthermore, water should be decontaminated before applying to reduce diseases to sensitive plants and should not be utilized for drinking uses.

5. Conclusions

The use of both intrinsic vulnerability data and quality one in a GIS environment proved to be a powerful tool for the groundwater management in arid and semi arid regions like Chebba-Mellouleche. The seven DRASTIC parameters: depth of groundwater, net recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity, were used to calculate the vulnerability of the study area. The results show that groundwater in Chebba – Mellouleche is characterized by four classes as follow: Moderate vulnerability ranked groundwater areas dominated the study area (>52%), which occupy middle of the study area, while (>38%) of the Chebba – Mellouleche aquifer is under high groundwater vulnerability.

The water susceptibility indexes show a low water quality, covering the majority of the study area. Indeed, there is a high similarity between the more hazardous pollution zones and the areas with low water quality. So, these scenarios proposed by this study could be used as a general guide for groundwater managers and planners.

The GIS technique has provided an efficient environment for analyses and high capabilities in handling a large quantity of spatial data. The susceptibility index parameters were constructed; classified and mapped employing various map and attribute GIS functions.

Fig. 8. Groundwater management scenarios proposed in the Chebba – Mellouleche Aquifer.

6.References

Aller, L., Bennet, T., Lehr, J.H., Petty, R.J., Hacket, G., 1987. DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeologic settings. US Environmental Protection Agency Report (EPA/600/2-87/035), Robert S. Kerr Environmental Research Laboratory, 455 pp.

Anon., 2007a. Tableaux climatologiques mensuels, stations de Mahdia (unpubl.). Annuaire de l'Institut de la Météorologie Nationale. Tunisia.

Anon., 2007b. Annuaires de surveillance de piézométrie, de nitrate et de salinité (unpubl.). Arrondissement des Ressources en Eaux de Mahdia. CRDA, Mahdia, Tunisia.

Anon., 2007c. Comptes rendus des forages et piézomètres de surveillance (unpubl.). Arrondissement des Ressources en Eaux deMahdia. CRDA,Mahdia,Tunisia

Anon., 2008. Carte numérique agricole de Mahdia 1:50,000.Official numerical file. at: http://www.carteagricole.agrinet.tn/GIS/33_MAHDIA/33_mahdia_fcarto/viewer.htm.

Bedir, M., 1995. Mécanismes géodynamiques des bassins associés aux couloirs de coulissement de la marge atlasique de la Tunisie: seismo- stratigraphie, seismo-tectonique et implications pétrolières. Thèse de doctorat ES- SCIENCES. Université de Tunis II, Tunisie, 414 pp.

Civita, M., Chiappone, A., Falco, M., Jarre, P., 1990. Preparazione della carta di vulnerabilita per la rilocalizzazione di un impianto pozzi dell´acquedutto di Torino. Proc. Ist. Conv. Naz. Protezione e Gestione del Vulnerability validation le acque sotterane: metodologie. Tecnologie e Obiettivi. Morano sol Panero. 2, 461–462.

CRDA Mahdia (Commissariat Régional du Développement Agricole de Mahdia), 2005. Annuaires d'exploitation des nappes phréatiques du gouvernorat de Mahdia.

Foster, S., Hirata, R., 1991. Groundwater pollution risk assessment. A methodology using available data; World Health Organisation (WHO)/Pan American Health Organisation (PAHO)/Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS), Technical Report, Lima, Perou, 2nd edition, 73 pp.

Neubert and Benabdallah., 2003. Système d'évaluation de la qualité des eaux souterraines SEQ – Eaux Souterraines. Rapport de présentation, version 0.1- Aout 2003, 75 pp.

Pusatli, T.O., Camur, Z.M., Yazicigil, H., 2009. Susceptibility indexing method for irrigation water management planning: applications to K. Menderes river basin, Turkey. J. Environ. Manage. 90, 341–347.

Rahman, A., 2008. A GIS based DRASTIC model for assessing groundwater vulnerability in shallow Aquifer in Aligarh, India. Appl. Geogr. 28, 32–53.

Saidi, S., Bouri, S., Ben Dhia, H., Anselme, B., 2009. A GIS-based susceptibility indexing method for irrigation and drinking water management planning: Application to Chebba–Mellouleche aquifer, Tunisia. Agricultural Water Management 96, 1683–1690.

Saidi, S., 2011.Contribution des approches paramétriques, cartographiques et statistiques à l'étude de la vulnérabilité du système aquifère phréatique de Mahdia. Thèse de doctorat. Université de Sfax, Tunisie, 254 pp.

Saidi, S., Bouri, S., Ben Dhia, H., 2011. Sensitivity analysis in groundwater vulnerability assessment based on GIS in the Mahdia-Ksour Essaf aquifer, Tunisia: a validation study. Hydrol. Sci. J. 56(2), 288–304.

Sophocleous, M.A., 1991. Combining the soil water balance and water level fluctuation methods to estimate natural groundwater recharge: practical aspects. Hydrol. J. 124, 229–241.

Trabelsi, R., 2008. Contribution a l'étude de la salinisation des nappes phréatiques côtières, cas du système de Sfax -Mahdia. Thèse de doctorat Université de Sfax, Tunisie 198 pp.

Van Stempvoort D., Ewert L., Wassenaar L.,1992. Aquifer vulnerability index: a GIS-compatible method for groundwater vulnerability mapping. Canadian Water Resources Journal, 18: pp 25-37.

WCCR (Water Contamination Control Regulations), 1991. Official Paper. Ankara, No. 19919.

World Health Organisation (WHO), 2006.. Guidelines for Drinking-water Quality. Recommendations, 3rd edition, vol. 1. WHO, ISBN 92 4 154696 4, 595 pp.

15

Soil, Water and Crop Management for Agricultural Profitability and Natural Resources Protection in Salt-Threatened Irrigated Lands

Fernando Visconti[1,2] and José Miguel de Paz[2]
[1]Desertification Research Centre – CIDE (CSIC, UVEG, GV), Valencia
[2]Valencian Institute of Agricultural Research - IVIA
Center for the Development of the Sustainable Agriculture - CDAS, Valencia
Spain

1. Introduction

In the world areas under arid, semi-arid or dry subhumid climate, i.e. where potential evapotranspiration (ETp) exceeds rainfall (R), water scarcity imposes limits on agricultural diversity and productivity. Nevertheless, soils of high potential productivity are also often found under such climates, usually associated to river lowlands where fresh water proximity has allowed irrigation development to produce crops of high nutritional and economic value. It has been estimated that one sixth of world cultivated area is irrigated (AQUASTAT, 2008). What is more important, one third of world agricultural production comes from irrigated lands, and this fraction is going to significantly increase in the upcoming years (Winpenny, 2003). The main restriction to meet all of the soil productive potential of areas where ETp exceeds R is, in addition to water scarcity, soil salinity.

Most of the water nowadays used for irrigation has first originated in rainfall (Fig. 1). The precipitation water on the continents can either infiltrate or run across the rocks and/or soil until it reaches a water body. The infiltrating water into the soils constitutes the soil moisture. It can percolate away from the rooting depth and eventually becomes groundwater. Throughout the soil and ground rocks, water reacts with minerals and as a consequence dissolves salts. Groundwater contributes a significant part of surface water and then, it adds the salts originated in soils and ground rocks. If groundwater does not spring, it continues its movement through the underground rocks usually increasing its load of salts. The salinization of the groundwater occurs due to a lengthy contact with ground minerals, and also because of other phenomena such as contact with saline strata, and seawater intrusion in coastal aquifers. Quite the opposite, the load of salts of surface waters is diluted by direct surface runoff. As a consequence, groundwaters are, in general, more saline than stream waters (Turekian, 1977). Whichever the case, when waters are applied to soils for irrigation, the salts in solution are also applied. Crops absorb water and exclude the major portion of salts, which are left behind in the soil. The absorbed water is transpired to the atmosphere and therefore salts concentrate in the soil solution. Nevertheless, when part of the irrigation water percolates through the bottom of the rooting depth, the salt build-up in soils does not increase indefinitely, it reaches an equilibrium point. This equilibrium point features a steady state, in which the mass of salts entering the soil equals the mass of salts leaving it. This equilibrium point is characterized by a constant medium-to-long-term-average soil salt content.

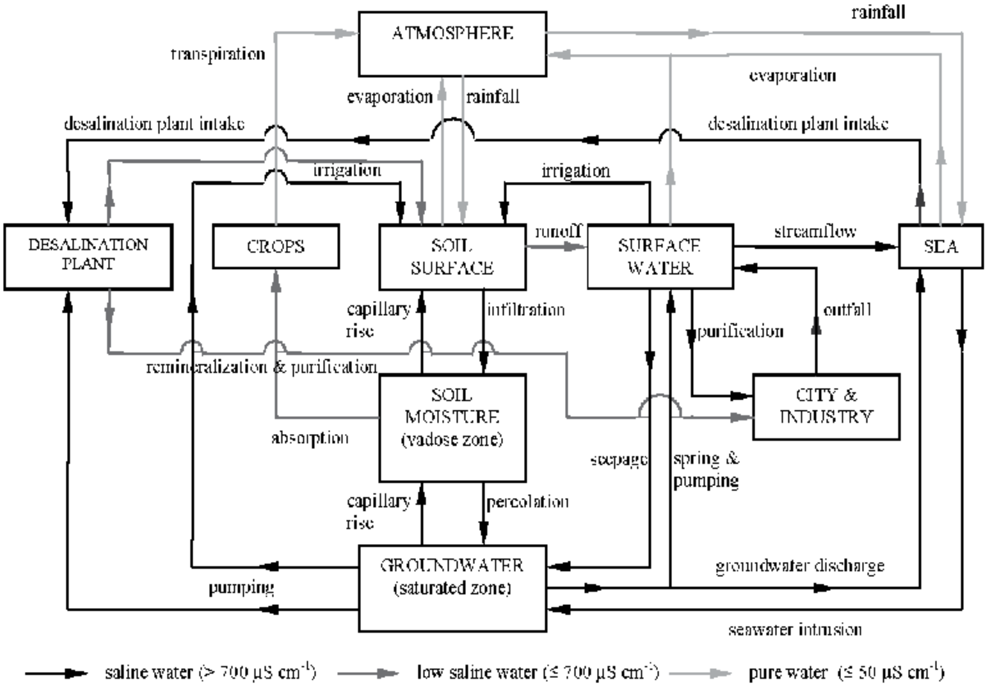


Fig. 1. Agrohydrological cycle

In arid, semi-arid and dry subhumid areas evapotranspiration exceeds precipitation and little water from rainfall percolates through the rooting depth. The more arid is climate the higher is the soil salinity featuring the equilibrium point. The excess of salts is defined with regards to plant tolerance. Plants absorb water from the soil solution, and therefore they respond to the salinity of the soil solution, rather than to the overall salinity of the soil. The salts dissolved in the soil solution decrease the potential of the soil water, which leads to a drought-like situation for plants. Given one plant species, as the soil solution salinity overcomes a plant-characteristic limit the crop suffers from drought and therefore yields decline. A good management of irrigation in arid to dry subhumid areas must provide the plants not only with the water they need to match the crop evapotranspiration, usually called the crop water requirement, but also with some excess water. This extra amount of water leaches, —in arid areas—, or helps to leach, —in semi-arid and dry subhumid areas—, part of the salts carried by the irrigation water itself. In addition to excess irrigation a good drainage must be assured to dispose of the percolating water. This way drainage complements irrigation to achieve a sustainable irrigation management.

The salinity of water systems including soil solution is made up mainly of only eight inorganic ions: sodium (Na^+), chloride (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sulphate (SO_4^{2-}), bicarbonate (HCO_3^-), potassium (K^+), and often also nitrate (NO_3^-). As charge bearing particles these ions give the water where they are dissolved the property to conduct electricity. Therefore the electrical conductivity at 25º C (EC_{25}), usually in units of dS m^{-1} or µS cm^{-1}, is commonly used as a measure of the salinity of water systems including soil solutions and irrigation waters. The ions just indicated combine to form several salts that differ in their solubility from the low to moderate solubility of calcite ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$) to the high solubility of the sodium and chloride salts. Precipitation of calcite and gypsum prevents the salinity of the soil solution from attaining harmful values when calcium, bicarbonate and / or sulphate are concentrated enough in the irrigation water. In addition to this favourable effect on salinity, calcite and gypsum have also a favourable effect on the soil cation balance. The combination of low salinity with a relatively high concentration of sodium with respect to calcium and magnesium, which is traditionally accounted for by the sodium adsorption ratio ($SAR = [Na^+]/([Mg^{2+}] + [Ca^{2+}])^{1/2}$), harms soil structure with consequences on water infiltration and soil aeration. High SAR values have also harmful effects on plants independently of salinity, because of the nutritional imbalance caused by the excessive concentration of sodium with regard to calcium. The weathering of calcite and/or gypsum from soil materials increases the calcium and sometimes magnesium content of the soil solution counteracting, on the one hand, the damage low salinity and high SAR have on soil structure, and on the other hand, counteracting the damage caused on the plant by a sodium high soil solution.

According to the sensitivity analysis of the steady-state soil salinity model SALTIRSOIL the expected average soil solution salinity depends on three main factors: climate, irrigation water salinity and irrigation water amount in this order (Visconti et al., 2011a). Traditionally, farmers have acted on these three factors to gain control on soil solution salinity.

Control over precipitation is out of human reach, however, farmers have some control on soil's climate. All the water saving practices aimed at increasing water infiltration and decreasing water evaporation help decrease also soil salinity (Zribi et al., 2011). Soil infiltration is traditionally enhanced by tillage and mulching with coarse materials of organic and inorganic origin. Soil evaporation is diminished through suppression of weed growth, irrigating at night and mulching with the same materials as before in addition to plastic mulches.

Regarding water quality, farmers have little control on the salinity of a given water body. Surface water has been traditionally the first and usually only option for irrigation. However, other water supplies have been made available throughout history thanks to collective initiatives led by irrigators unions, governments and enterprises. Rainwater harvesting (Huang et al., 1997; Abdelkhaleq & Ahmed, 2007) and water diversions have been used in many instances as non-conventional water supplies well before the 20th century. Groundwater has been used for millennia to irrigate where surface water was absent. However, the intensive exploitation of groundwater resources for irrigation did not occur until the late 19th century when the powerful machinery necessary for drilling and pumping water from depths beneath 8 m was available (Narasimhan, 2009). Other non-conventional water resources have arisen during the 20th century such as waste and reclaimed waters of urban, industrial and mining origin and also desalinated waters. Each one of these water supplies is characterised by a different composition and therefore salinity and SAR. Traditionally farmers have not been aware of these differences until the effects on plants have revealed themselves. Nowadays measurement of, at least, surface water salinity is often routinely carried out by government authorities and irrigators unions. Although farmers cannot change the quality of a water body, modern irrigation methods have allowed them changing the quality of the water actually used for irrigation. This is usually done by fertigation, but also by blending waters from different sources in irrigation reservoirs. The same technology available for fertigation can be used for adding chemicals such as gypsum or mineral acids to decrease the soil solution SAR if necessary.

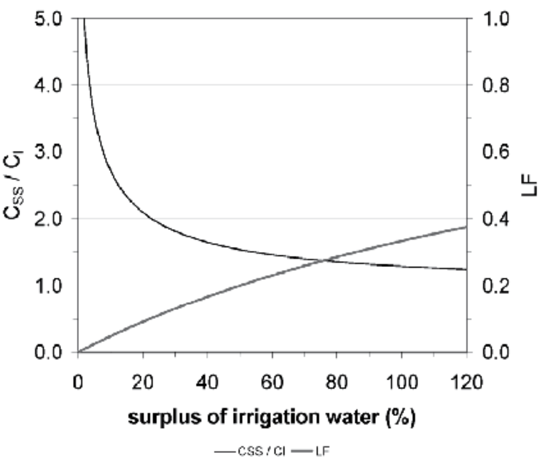


Fig. 2. Leaching fraction (LF) and relative salinity of the soil solution (C_{SS} / C_I) as function of the surplus of irrigation water following a 40:30:20:10 root water uptake pattern and a quotient R / ET_c of 0.5. Equations after Hoffman & Van Genuchten (1983)

The irrigation water amount is not as influential on soil salinity as climate and irrigation water quality. However, this factor has been traditionally considered as the one through which the farmer can exert more control over soil salinity. The idea that irrigation water leaches soil salts has established itself in many places as the popular belief that the more you irrigate the more salts you leach out of the soil. However, the relationship between soil salinity and irrigation water amount is far from being linear. The relationship is in fact a rational in which once the sum of rainfall and irrigation have matched the crop water requirement the soil solution salinity rapidly decreases with irrigation water surpluses of only 10 to 20% (Fig. 2). From 30% on, the soil solution salinity hardly decreases. It tends asymptotically to a limit which depends on climate, specifically the quotient rainfall to evapotranspiration, and irrigation water salinity.

Not only excess overirrigation constitutes a waste of water, which is on itself a severe problem in the present global scenario of scarcity and competition for safe water resources. As occurs with overfertilization it can be self-defeating. The amount of irrigation water must not surpass the limits imposed not only by the availability of water resources, but also by the capability of the drainage systems and the hydrology of the whole area where the crops are grown. In the medium to long term overriding the natural and man-made irrigation and drainage limits gives rise to serious on and off-farm problems of degradation of lands and water bodies (rivers, lakes and aquifers). Among these problems caused by overirrigation we find the rise of the water table underlying the crop fields, which impedes the soil leaching and leads to waterlogging and soil salinization. Furthermore, overirrigation increases the amount of drainage effluents, which are usually loaded with salts, nutrients and agrochemicals. This constitutes on the one hand a waste of farm investment, and on the other, a potential damage to the natural water bodies because of salinization, eutrophication and pollution.

Provided excess overirrigation is far from being adequate either in terms of agricultural profitability or natural resources protection, the question is how much water in excess of the crop water requirement is necessary to keep soil salts below the limit from which yields will decline. This question has been traditionally answered performing the following calculation (Eq. 1), where IR, R and ET_c are for the irrigation requirement, rainfall and crop evapotranspiration respectively, all in units of L T^{-1}, usually mm yr^{-1}.

$$IR = \frac{ET_c}{1 - LR} - R \tag{1}$$

Providing the amount of water that percolates through the bottom of the root zone is the soil drainage (D), the fraction of the infiltrating water ($I + R$) which becomes the soil drainage is known as the leaching fraction ($LF = D / (I + R)$) where I is for the actual irrigation. In Eq. 1 LR stands for the leaching requirement, which is defined as the minimum leaching fraction necessary to leach the soil salts below a limit considered harmful for a given crop. In order to optimize the irrigation rates the calculation of the leaching requirement has been the objective of several simulation models during the last 50 years.

The irrigation scheduling based on the calculation of a leaching requirement assume at least that i) the steady-state hypothesis is valid enough for the irrigation project, and ii) that the farmer has enough control over the irrigation application to adjust the quantity of water delivered to the soil. The steady-state hypothesis has been criticized because soil salinity fluctuates heavily in the short term following mostly the soil water content. Nevertheless, the leaching requirement is not intended to be a parameter useful at little scale either in time or spatial terms. Rather the leaching requirement is useful for irrigation planning from months to years, and from plots to irrigation districts. Ideally, how the irrigation rates and scheduling should be applied would start from the knowledge of the maximum soil salinity tolerable by the crop or crops to be cultivated during the whole growing season. Next the annual leaching requirement would be assessed with a model such as the traditional LR model (Rhoades, 1974), the WATSUIT (Rhoades & Merrill, 1976) or another developed for the same purpose. Accurate enough predictions of soil salinity only demand i) annual averaged boundary conditions, ii) a coarse spatial discretization, and the simulation of iii) cation exchange and iv) gypsum dissolution–precipitation (Schoups et al., 2006). WATSUIT has the characteristics (i) and (ii) and simulates gypsum equilibrium chemistry. Therefore, despite the last version of WATSUIT is 20 years old, it continues to be a benchmark for developing irrigation guidelines for salt-threatened soils. Once the leaching requirement is known, the required amount of irrigation water can be calculated by means of Eq. 1. Nevertheless, as weather varies from year to year how this amount of water has to be applied demands knowledge about soil water content. This knowledge can be based on meteorological data and soil water content measurements. All these in addition to farmers' experience should guide the application of irrigation water.

The model SALTIRSOIL was originally developed for the simulation of the annual average soil salinity in irrigated well-drained lands (Visconti et al., 2011b). It has characteristics similar to WATSUIT. The input data to the model included i) climate data such as monthly values of reference evapotranspiration (ET_0) and amount and number of days of rainfall, ii) water quality data such as yearly average concentrations of the main ions, iii) irrigation scheduling data such as monthly values of irrigation amount, number of irrigation days and percentage of wetted soil, iv) crop data such as monthly or season basal crop coefficients, percentage of canopy ground cover and sowing and harvest dates for annual crops, and finally v) chemical and hydrophysical soil data. The SALTIRSOIL was intended to be a predictive model, however, it can be used for irrigation and soil management. The best irrigation scheduling for keeping soil salinity below some critical value can be found batch running the same simulation while changing the irrigation rates and schedule.

Following the methodology just described the SALTIRSOIL model is useful to search for the most adequate irrigation rates and scheduling in order not to surpass an average-annual limit of soil salinity. This is interesting but it could be improved without any loss of the original applicability of the model, i.e. optimum ratio of information to data requirements. This has been done adapting the SALTIRSOIL algorithms for the monthly average calculation of soil salinity.

In the following the new algorithms implemented in SALTIRSOIL for the calculation of the monthly average soil salinity in irrigated well-drained lands, and the use of this new SALTIRSOIL, from now on referred to as the SALTIRSOIL_M model, for the development of optimum guidelines for soil, water and crop management in irrigated salt-threatened areas will be shown. These guidelines will be discussed in the framework of the different productive and environmental challenges irrigation faces in a relevant place in SE Spain.

2. SALTIRSOIL_M: A new tool to assess monthly soil salinity and for irrigation management in salt-threatened soils

The SALTIRSOIL was developed as a deterministic, process-based and capacity-type model. The development of the SALTIRSOIL model started from the characteristics that made the steady-state models WATSUIT (Rhoades & Merrill, 1976) and that of Ayers & Westcot (1985) so useful for the leaching requirement calculation and for assessing the water quality for irrigation.

Steady-state models for soil salinity start from the hypothesis that soil water and salt content keep constant through time. These conditions could only be true if water would continuously flow through soil. This is never the case because irrigation and rainfall are discontinuous processes. Modern transient-state models take into account the time variable, which makes them able to give accurate values of soil water and salt content as has been shown by Goncalves et al. (2006) for the HYDRUS model. Despite these advantages, transient-state models are seldom used outside of research applications because they demand data not available or difficult to obtain. The time variable can be, however, implemented in soil salinity steady-state models while preserving their basic assumptions. This has been shown by Tanji & Kielen (2002), and on a daily basis by Isidoro & Grattan (2011).

The original SALTIRSOIL model has been adapted for the monthly calculation of soil salinity to give the SALTIRSOIL_M model. Therefore the new SALTIRSOIL_M performs a water and salt balance in monthly steps. In the simulations the soil is divided in a number of layers selected by the user. In each simulation the water balance is calculated first, and then the soil solution concentration factor of the soil solution regarding the irrigation water in each layer. An average soil solution concentration factor for each month is calculated afterwards. The composition of the irrigation water each month is multiplied by the corresponding monthly average concentration factor and the calculation of the composition of the soil solution at different soil water contents and allowing to equilibrate with soil CO_2, calcite and gypsum is carried out. Finally the electrical conductivity at 25 ^oC is assessed. The SALTIRSOIL model concepts for the annual calculation of the soil salinity have been described in detail elsewhere (Visconti et al., 2011b). Here only the calculations implemented in SALTIRSOIL_M for the monthly balance of salts in the soil solution are shown.

2.1 Monthly mass balance of salts in the soil solution

Let the soil be split in a number n of layers, and let the shallowest soil layer be the layer 1. The mass of a conservative solute in the solution of the layer 1 in the month i ($m_{i,1}$) can be calculated from Eq. 2.

$$m_{i,1} = m_{i-1,1} + I_i C_{Ii} - D_{i,1} C_{i,1} \tag{2}$$

Where $m_{i\text{-}1,1}$ is the mass of the solute in layer 1 the previous month (i – 1), I_i and $C_{i,1}$ are, respectively, the amount of irrigation water and the concentration of the conservative solute the month i, and $D_{i,1}$ and $C_{i,1}$ are the drainage from the layer 1, and the concentration of the solute in the soil water in that layer.

The concentration of the conservative solute in the soil solution of the layer 1 is obtained through Eq. 3 where the mass of the solute given by Eq. 2 has been divided by the average water content of that layer the month i ($V_{i,1}$).

$$C_{i,1} = C'_{i-1,1} + \frac{I_i C_{Ii}}{V_{i,1}} - \frac{D_{i,1} C_{i,1}}{V_{i,1}} \tag{3}$$

Equation 3 can be reorganized to isolate the concentration of the solute as a function of the rest of variables (Eq. 4).

$$C_{i,1} = \frac{C'_{i-1,1} V_{i,1} + I_i C_{Ii}}{V_{i,1} + D_i} \tag{4}$$

In Eq. 3 and Eq. 4 $C'_{i-1,1}$ is the mass of solute the previous month divided by the volume of soil water in that layer the present month i. This variable can be expressed in terms of the concentration of the solute in the layer 1 the previous month considering the quotient of the soil water the previous month and the present month (Eq. 5).

$$C'_{i-1,1} = C_{i-1,1} \frac{V_{i-1,1}}{V_{i,1}} \tag{5}$$

Eq. 5 is substituted in Eq. 4 and after dividing by C_{Ii} Eq. 6 is obtained for the calculation of the concentration factor of the soil solution in layer 1 the month i at average field water content ($f_{i,1} = C_{i,1} / C_{Ii}$).

$$f_{i,1} = \frac{f_{i-1,1} V_{i-1,1} \frac{C_{Ii-1}}{C_{Ii}} + I_i}{V_{i,1} + D_{i,1}} \quad (6)$$

Similarly to Eq. 2 the mass of a conservative solute in the soil water of a layer j ($j \neq 1$) is calculated with the following equation (Eq. 7).

$$m_{i,j} = m_{i-1,j} + D_{i,j-1} C_{i,j-1} - D_{i,j} C_{i,j} \quad (7)$$

Where $D_{i,j}$ and $D_{i,j-1}$ are respectively the drainage water the present month i from the layer j and from its overlying layer (j – 1), and $C_{i,j}$ and $C_{i,j-1}$ are the solute concentration the present month i in the layer j and in its overlying layer j - 1. Following similar steps to those heading to Eq. 6 we get to Eq. 8 for the calculation of the concentration factor of a conservative solute in the soil water of a layer j in the month i.

$$f_{i,j} = \frac{V_{i-1,j} f_{i-1,j} \frac{C_{Ii-1}}{C_{Ii}} + D_{i,j-1} f_{i,j-1}}{V_{i,j} + D_{i,j}} \quad (8)$$

2.2 Development of irrigation recommendations: A case study for several crops in the traditional irrigated area of *Vega Baja del Segura* (SE Spain)

The SALTIRSOIL_M model has been used to develop irrigation recommendations in the relevant traditional irrigated district of *Vega Baja del Segura* (SE Spain).

The *Segura* River and *Baix Vinalopó* lowlands together represent one of the most important agricultural areas in Spain. More than 90% of the land is irrigated and approximately 80% of it is salt-affected (de Paz et al., 2011). The main crops that cover 61% of the irrigated area are citrus such as orange, mandarin and Verna lemon (*Citrus sinensis*, *Citrus reticulata* and *Citrus limon* (L) Burm f.) grafted onto various different rootstocks. The moderately salt-tolerant Sour Orange (*Citrus aurantium* L.) and especially Cleopatra mandarin (*Citrus reshni Hort. ex Tan.*) are used as rootstocks for more than 60% of citrus. Vegetables (including tubers) cover 16% of the area. These are globe artichoke (*Cynara scolymus* L.), lettuce (*Lactuca sativa* L.), melon (*Cucumis mello* L.), broccoli (*Brassica oleracea*, Botrytis group), and potato (*Solanum tuberosum* L.). Non-citrus fruit trees cover 12% of the area, specifically almond (*Prunus dulcis*), pomegranate (*Punica granatum* L.) and date palm (*Phoenix dactylifera* L.).

The *Segura* River and *Baix Vinalopó* lowlands comprise several irrigation districts, each one of them featured by different irrigation systems, crops and water supplies. The traditional irrigation district of *Vega Baja del Segura* (Fig. 3) is one of the most important because of the use of water resources, which has been estimated between 80 and 120 hm^3 yr^{-1} (Ramos, 2000), number of farmers, productivity, history and the large stretch of land, which amounts up to approximately 20000 ha from which 15000 ha are actually irrigated each year (MMA, 1997). The average Penman-Monteith reference evapotranspiration and precipitation are 1215 and 385 mm yr^{-1}, respectively. In this irrigation district the distribution of horticultural and tree crops is 70-30% (MMA, 1997). The main irrigation water supply in the irrigation district is the *Segura* River itself. Although new irrigation projects use drip systems, at least 50% of the area is still irrigated by surface.

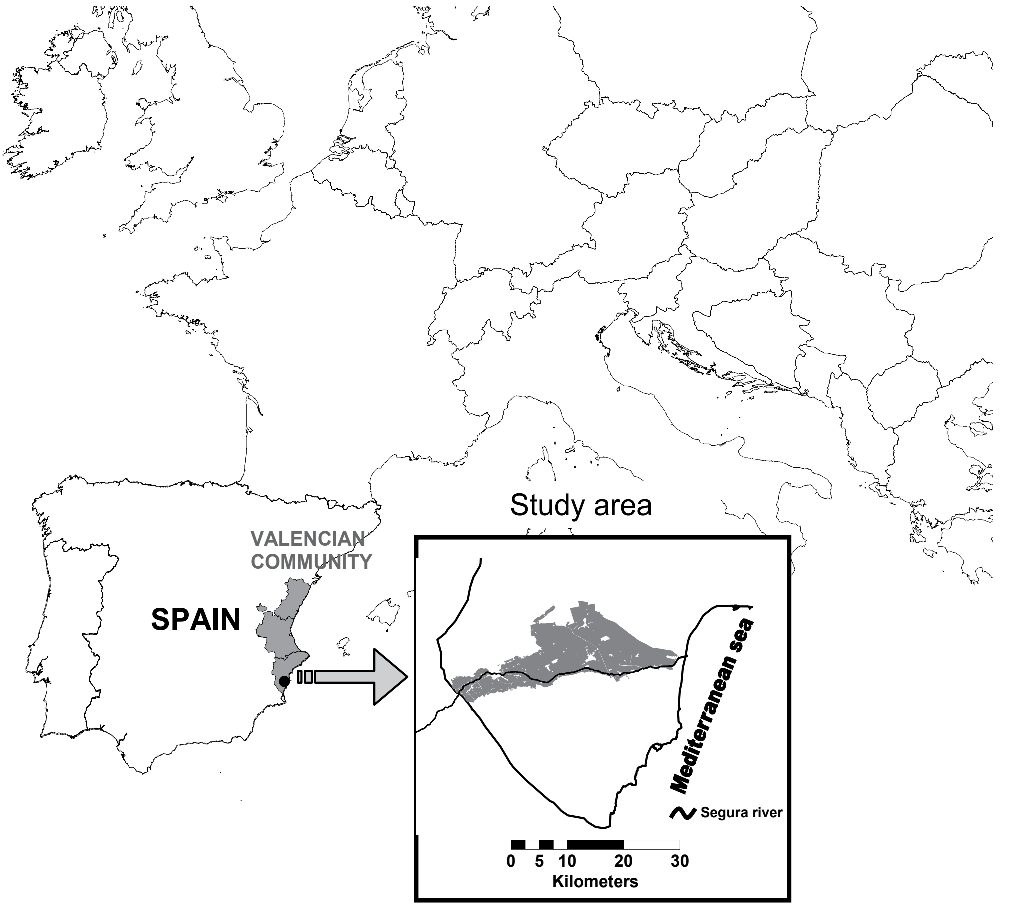


Fig. 3. Location of the Traditional Irrigation Area of the *Vega Baja del Segura*

Month	pH	Alk.	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	NO_3^-	SO_4^{2-}	EC_{25}
Jan	7.75	5.75	20.84	0.52	6.24	5.87	17.22	0.59	9.62	3.91
Feb	7.77	5.85	21.84	0.50	7.22	6.93	19.53	0.52	11.33	4.19
Mar	8.10	5.42	20.76	0.57	7.34	7.09	21.81	0.66	12.41	4.41
Apr	7.85	5.81	24.67	0.63	7.49	7.47	24.14	0.51	12.03	4.92
May	7.80	5.78	22.13	0.45	6.60	6.77	20.27	0.34	9.77	4.49
Jun	7.48	5.03	16.94	0.44	5.80	5.74	16.87	0.22	9.56	3.51
Jul	7.50	5.93	39.71	0.68	7.13	8.21	39.83	0.38	12.42	6.39
Aug	7.63	5.16	30.42	0.48	5.81	6.23	28.10	0.38	10.92	4.89
Sep	7.78	4.69	16.65	0.40	5.03	5.16	15.25	0.24	7.90	3.38
Oct	7.60	5.37	27.15	0.60	6.82	6.68	23.77	0.65	11.52	4.46
Nov	7.88	4.96	19.86	0.52	5.88	5.88	17.49	0.65	10.19	3.87
Dec	7.64	5.02	20.58	0.52	6.54	6.54	18.80	0.64	11.15	4.09
Avg.	7.73	5.40	23.46	0.53	6.49	6.55	21.92	0.48	10.73	4.37

Table 1. Monthly characteristics of the Segura River water during the three year period 2007-2009. All ion concentrations in mmol L^{-1}, EC_{25} in dS m^{-1} and alkalinity (Alk.) in $mmol_C$ L^{-1}

The *Segura* River goes through the traditional irrigated district of *Vega Baja del Segura*, and there exhibits annual averages of electrical conductivity at 25 ºC (EC_{25}) and SAR of 4.3 dS m^{-1} and 6.3 (mmol $L^{-1})^{1/2}$, respectively. However, the EC_{25} and SAR remarkably fluctuate through the year (Table 1) following the cycle of water releases from upstream dams (Ibáñez & Namesny, 1992). From late autumn till mid spring water is slowly released from dams to maintain environmental flow, which includes winter irrigation. Important water releases start in spring, and along with them the EC_{25} slightly increases because the low EC_{25} water (≈ 1.2 dS m^{-1}) of the upstream dams helps sweep the outfalls from the sewage treatment plants and irrigation returns through a river that otherwise presents a constant but low base-flow. The next months, the EC_{25} decreases until it reaches a minimum in June. During July the EC_{25} increases again because the irrigation returns from upstream lands increase the river flow and because water releases stop during this month. In late July and early August the important water releases resume and the EC_{25} decreases again until it reaches another minimum in September. Then the important water releases stop until the next year and the EC_{25} attains a maximum during October because of the autumn rainfalls. This is the most important rainfall season in the area and it effectively leaches the salts from the lands as the increase in the EC_{25} of the river shows. Because of the correlation between electrical conductivity and sodium adsorption ratio in the *Segura* River the SAR follows a parallel fluctuation to the EC_{25}.

2.2.1 Set up of simulations

The soil saturation extract composition of the soils of the *Vega Baja del Segura* was simulated with SALTIRSOIL_M under ten different crops. These were three horticultural crops and seven tree crops. The horticultural crops were globe artichoke, grown from October 1st until July 8th, and rotation of melon and broccoli, from September 14th until January 27th, and melon also from April 1st until August 19th and potato from September 14th until January 22nd. The tree crops were date palm, sweet orange, lemon grafted onto sour orange, lemon grafted onto Mandarin Cleopatra, lemon grafted onto *Cytrus Macrophylla*, Verna lemon and pomegranate. These ten crops are representative of at least 75% of the agriculture of the *Vega Baja del Segura* and according to their threshold-slope functions of yield against electrical conductivity of the saturation extract (EC_{se}) they exhibit different tolerances to soil salinity (Figure 4). Except for date palm and globe artichoke which are from moderately tolerant to tolerant, the rest of crops are moderately sensitive to soil salinity. Pomegranate is between moderately sensitive to moderately tolerant defining in fact the limit between both categories. The data on soil, climate, threshold-slope functions and basal crop coefficients used in the simulations can be found in Visconti et al. (2012).

Simulated crop	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Tot**
Artichoke	1	25	32	70	89	81	31	7	0	0	4	0	339
Mel.-Broccoli	0	0	0	34	65	110	122	68	0	0	8	2	410
Melon-Potato	0	0	0	34	65	109	121	68	0	0	20	6	423
Date palm	2	23	27	73	97	135	139	122	22	0	18	3	660
Sweet orange	0	15	14	50	65	90	98	93	1	0	13	0	440
Lemon trees	0	9	4	39	51	81	84	72	0	0	7	0	347
Pomegranate	0	0	0	44	66	102	106	92	2	0	2	0	415

Table 2. Crop water requirements in mm calculated with SALTIRSOIL

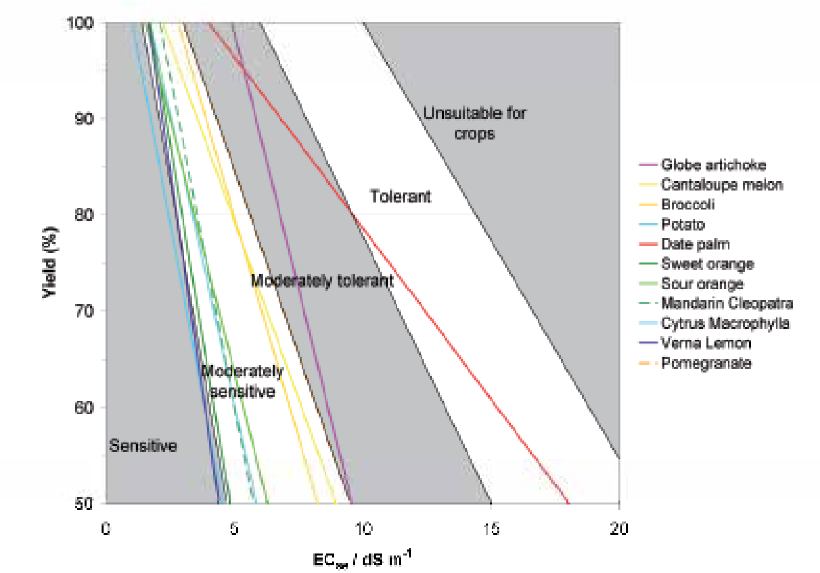


Fig. 4. Threshold-slope functions of yield versus electrical conductivity of the soil saturation extract (EC_{se}) for the crops simulated with SALTIRSOIL_M in the *Vega Baja del Segura.* Categories after Maas & Hoffman (1977)

For each one of the crops the annual leaching requirement was assessed in the following way. The crop water requirement, i.e. the crop evapotranspiration, was first calculated with the SALTIRSOIL (Table 2). Then starting with the simulation in which the irrigation dose was set equal to between – 50 to – 30% of the crop water requirement, several simulations were carried out gradually increasing the annual irrigation water amount in 5% steps. Once the batch of simulations was finished the monthly values of EC_{25} in each simulation were averaged to obtain the corresponding annual EC_{25}. As the annual LF is also calculated by the SALTIRSOIL_M, this allowed us to have the graph of annual EC_{se} against LF. The electrical conductivity for 90% yield, which is called EC_{90}, was then calculated from the corresponding threshold-slope functions (Fig. 4). For the horticultural crop rotations the EC_{90} was calculated for both crops, and the value for the most sensitive was used, i.e. the lower EC_{90}. These were melon and potato for the melon-broccoli and melon-potato rotations respectively. The values of EC_{90} (Table 3, second column) were then interpolated in their corresponding graphs of annual EC_{se} against LF to obtain the annual leaching fraction for 90% yield (LF_{90}). This value was taken as the leaching requirement, i.e. LR = LF_{90}.

2.2.2 Results of the simulations

The leaching requirements calculated with the SALTIRSOIL_M were between 0.08 and more than 0.99 (Table 3, last column). The moderately tolerant to tolerant globe artichoke and date palm presented leaching requirements of 0.08 and 0.09 respectively. The moderately sensitive to tolerant pomegranate presented a leaching requirement of 0.19. The melon-potato, sweet orange, lemon grafted onto sour orange and onto *Cytrus Macrophyla*, and Verna lemon presented values higher than 0.99. This means that a yield of at least 90% can not be achieved for these crops in the area when irrigating with *Segura* River water. With a leaching requirement of 0.75 the only citrus that could be grown for at least 90% yield with *Segura* River water would be those grafted onto the Mandarin Cleopatra rootstock. With a leaching requirement of 0.50 the succession of melon and broccoli could also be grown for at least 90% yield.

The results of the SALTIRSOIL_M model for the annual leaching requirement were compared with previously calculated leaching requirements with the WATSUIT and the SALTIRSOIL models (Visconti et al., 2012). The SALTIRSOIL_M calculates lower leaching requirements than the SALTIRSOIL as is shown in Table 3. The leaching requirements calculated with SALTIRSOIL_M are also lower than the corresponding values calculated with WATSUIT when dealing with the moderately sensitive to tolerant crops. When dealing with moderately sensitive crops the leaching requirements calculated with SALTIRSOIL_M are higher than the values calculated with WATSUIT.

Simulated crop	**EC_{90} / dS m^{-1}**	**WATSUIT**	**SALTIRSOIL**	**SALTIRSOIL_M**	
			Surface	**Surface**	**Drip**
Globe artichoke	5.83	0.13	0.10	0.08	0.07
Melon-broccoli	3.55	0.42	0.67	0.50	0.47
Melon-potato	2.53	0.79	> 0.99	> 0.99	> 0.99
Date palm	6.80	0.09	0.09	0.09	0.08
Sweet orange	2.33	0.92	> 0.99	> 0.99	> 0.99
Lemon onto SO	2.48	0.82	> 0.99	> 0.99	> 0.99
Lemon onto MC	2.81	0.65	> 0.99	0.75	0.73
Lemon onto CM	1.72	> 0.99	> 0.99	> 0.99	> 0.99
Verna Lemon	2.19	> 0.99	> 0.99	> 0.99	> 0.99
Pomegranate	4.30	0.27	0.25	0.19	0.17

Table 3. Electrical conductivities for 90% yields (EC_{90}) and corresponding leaching requirements calculated with the WATSUIT, SALTIRSOIL and SALTIRSOIL_M models

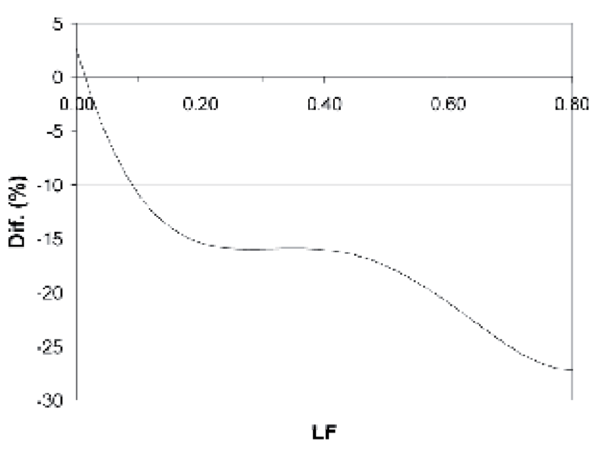


Fig. 5. Average percentage difference (Dif. (%)) between the EC_{se} calculated with SALTIRSOIL and SALTIRSOIL_M as a function of the leaching fraction (LF)

The SALTIRSOIL_M calculates average annual soil salinities between 10 and 30% lower than the SALTIRSOIL as is shown in Fig. 5. Transient-state models calculate lower soil salinities than steady-state models (Corwin et al., 2007). This fact makes the leaching requirements calculated with transient-state models to be lower than the leaching requirements calculated with steady-state models (Corwin et al, 2007; Letey et al., 2011). The implementation of the time variable as simple monthly steps in the SALTIRSOIL_M model has suffice to have soil salinities very similar to those calculated with other more complex and data-demanding transient-state models.

2.2.3 Proposal of irrigation recommendations

The irrigation requirements for the crops for which the 90% yield is achievable are between the 357 mm yr^{-1} of the moderately tolerant artichoke and the 2345 mm yr^{-1} of the moderately sensitive lemon grafted onto the Mandarin Cleopatra rootstock (Table 4). According to the *Segura* Valley Authority (MMA, 1997) and Ramos (2000) the average availability of water for irrigation from the *Segura* River in the traditional irrigated area of *Vega Baja del Segura* can be estimated between 530 and 800 mm yr^{-1}. Assuming that the maximum availability of irrigation water from the *Segura* River is never going to be higher than 800 mm yr^{-1}, the resulting soil salinity (EC_{se}) would be between the EC_{90} of the tolerant date palm (6.8 dS m^{-1}) and the 3.2 dS m^{-1} of the lemon trees (Table 4). The surface weighted average soil salinity would result to be 4.4 dS m^{-1}, with a monthly maximum of 7.3 dS m^{-1} for date palm orchards and a minimum of 2.8 dS m^{-1} for lemon trees orchards. Given this availability of water for irrigation the surface weighted average yield would be 82% with a minimum of 63% for sweet orange orchards. These yields would be achieved with an average 683 mm yr^{-1} of water, i.e., 102 hm^3 yr^{-1} for the whole irrigation district.

In the traditional irrigated area of *Vega Baja del Segura* almost all of the land is equipped with underground pipelines to collect of the waters that percolate through the rooting depth. The drainage waters are disposed by means of a hierarchical system of canals. The major canals are called *azarbes* and they go through the *Vega Baja* more or less parallel to the *Segura* River bed until they pour into the river mouth itself. According to the SALTIRSOIL_M calculations the drainage effluents from the traditional irrigated area of the *Vega Baja del Segura* would be between 61 and 513 mm yr^{-1}, with a surface weighted average of 338 mm yr^{-1}. This would amount to 51 hm^3 yr^{-1} of drainage effluents from the whole district. These drainage effluents would present a salinity (EC_{dw}) between 7 and 24 dS m^{-1}, while the sodicity (SAR_{dw}) would be between 9 and 24 (mmol $L^{-1})^{1/2}$ with weighted averages of 8.3 dS m^{-1} and 10.4 (mmol $L^{-1})^{1/2}$, respectively. These drainage effluents are, thus, high in EC and SAR and become an environmental concern. In spite of their salinity and sodicity, along their way through the district the irrigation returns from upstream lands are usually used again for irrigation (Abadía et al., 1999). Accordingly, on the one hand the district's irrigation water requirement would be less as an important part of the drainage water is reused, and on the other hand, the irrigation application in the moderately tolerant to tolerant crops in the area, i.e. artichoke, date palm and pomegranate, should increase a bit in order to have drainage effluents lower in salts and sodium. It is reasonable to think that both facts would compensate each other and the appropriate irrigation requirement for the whole area should not be less than 102 hm^3 yr^{-1}. Regarding the citrus trees the moderately sensitive sweet and *Cytrus Macrophyla* oranges and Verna lemon should be grafted onto more tolerant rootstocks such as Mandarin Cleopatra, sour orange and other similar to these. With these rootstocks citrus yields of 80-85% would be achievable with just 800 mm yr^{-1} of Segura River water. These little decrements in citrus yields are usually reflected in decreased average fruit size, however, they are also accompanied by higher juice sugar and acid contents (Grieve et al., 2007). Increments in fruit quality with slight salinity stress have been described for other fruits including melon (Bustan et al., 2005).

The traditional irrigated area of *Vega Baja del Segura* has been irrigated by surface for centuries. Nevertheless, since the early nineties localized irrigation systems are slowly replacing them. Localized irrigation systems are characterized by i) more frequent irrigations, ii) less water application in each irrigation, and iii) less wetted area. The effect of these three variables can be simulated with SALTIRSOIL and SALTIRSOIL_M.

Drip irrigation was simulated in SALTIRSOIL_M decreasing the wetted soil area from 40% to 3% and multiplying the number of irrigation days a year by 6. The irrigation amount was kept constant.

Simulated crop	IR_{90}	I_{rec}	ET_a	D	EC_{se}	EC_{se}min	EC_{se}max	Y(%)	EC_{dw}	SAR_{dw}
Globe artichoke	357	357	681	61	5.83	5.17	6.64	90	17.7	18.0
Melon-broccoli	1066	800	731	453	3.92	3.37	4.57	87	7.48	9.79
Melon-potato	—	800	748	437	3.97	3.36	4.61	73	7.68	9.93
Date palm	744	744	1032	97	6.80	6.55	7.26	90	23.9	24.3
Sweet orange	—	800	801	383	4.04	3.45	4.60	63	8.84	10.9
Lemon onto SO	—	800	672	513	3.22	2.75	3.82	82	7.27	9.41
Lemon onto MC	2345	800	674	510	3.22	2.75	3.82	84	7.27	9.41
Lemon onto CM	—	800	672	513	3.22	2.75	3.82	69	7.27	9.41
Verna Lemon	—	800	672	513	3.22	2.75	3.82	71	7.27	9.41
Pomegranate	528	528	736	177	4.30	3.55	5.04	90	11.5	13.1
AVERAGES	—	[a]683	[a]729	[a]338	[a]4.40	—	—	[a]82	[b]8.3	[b]10.4

[a]Surface weighted average (70% horticultural, 30% trees), [b]Surface and drainage weighted average

Table 4. Irrigation requirement for 90% yield (IR_{90}), recommended irrigation (I_{rec}), actual evapotranspiration (ET_a), and drainage (D) all in mm yr^{-1}, EC (dS m^{-1}) and SAR ($(mmol\ L^{-1})^{1/2}$) of the saturation extract and of the drainage water calculated for surface irrigation

The leaching requirement for drip irrigation slightly decreases regarding surface irrigation as is shown in Table 3. This occurs because drip irrigation minimizes the evaporation of water from the soil. Therefore, the actual evapotranspiration would drop from 729 to 683 mm yr^{-1} (Table 4 and Table 5), thus increasing the drainage from 338 to 369 mm yr^{-1}. If the whole irrigation district used drip irrigation systems the irrigation water demand would drop to 667 mm yr^{-1}, i.e., 100 hm^3 yr^{-1}. The soil salinity would also drop to 4.3 dS m^{-1}, with a maximum of 7.5 dS m^{-1} and a minimum of 2.6 dS m^{-1}. Furthermore the yields for citrus would rise and the overall average relative yields would keep or increase. On the other hand the amount of drainage effluents would rise to 55 hm^3 yr^{-1} with average electrical conductivity and sodium adsorption ratio of 8.4 dS m^{-1} and 10.8 $(mmol\ L^{-1})^{1/2}$, i.e., with salinity and sodicity slightly higher than when using surface irrigation systems.

Simulated crop	IR_{90}	I_{rec}	ET_a	D	EC_{se}	EC_{se}min	EC_{se}max	Y(%)	EC_{dw}	SAR_{dw}
Globe artichoke	317	317	649	52	5.83	5.09	6.71	90	19.30	19.2
Melon-broccoli	820	800	677	508	3.67	3.03	4.35	89	6.99	9.35
Melon-potato	—	800	694	491	3.72	2.99	4.40	76	7.14	9.46
Date palm	688	688	986	87	6.80	6.47	7.51	90	24.52	24.9
Sweet orange	—	800	730	454	3.70	3.04	4.33	68	7.85	9.73
Lemon onto SO	—	800	632	553	3.12	2.60	3.73	83	6.93	9.12
Lemon onto MC	2024	800	631	554	3.12	2.60	3.73	86	6.93	9.12
Lemon onto CM	—	800	632	553	3.12	2.60	3.73	70	6.93	9.12
Verna Lemon	—	800	632	553	3.12	2.60	3.73	73	6.93	9.12
Pomegranate	435	435	683	136	4.30	3.52	5.29	90	12.21	13.9
AVERAGES	—	[a]667	[a]683	[a]369	[a]4.26	—	—	[a]83	8.4	10.8

[a]Surface weighted average (70% horticultural, 30% trees), [b]Surface and drainage weighted average

Table 5. Irrigation requirement for 90% yield (IR_{90}), recommended irrigation (I_{rec}), actual evapotranspiration (ET_a), and drainage (D) all in mm yr^{-1}, EC (dS m^{-1}) and SAR ($(mmol\ L^{-1})^{1/2}$) of the saturation extract and of the drainage water calculated for drip irrigation

3. Conclusion

Modern irrigation faces a problem of optimization to attain maximum agricultural profitability with minimum damage to natural resources. This demands a precise use of water in the fields, which can be carried out combining i) modelling with ii) monitoring of soil water and salinity, and with iii) irrigation manager or advisor experience. Validated soil salinity models can assist on the development of optimum guidelines for the use of water in salt-threatened areas. The SALTIRSOIL_M model has been developed from the SALTIRSOIL model for the calculation of soil solution major ion composition, pH and electrical conductivity in monthly steps. The time variable has been included in the SALTIRSOIL_M preserving the original capabilities of the SALTIRSOIL model, i.e. maximum reliability-to-data-requirements. In fact no additional data is needed to run SALTIRSOIL_M regarding the original SALTIRSOIL. Just as occurred with the SALTIRSOIL more accurate results can be obtained if detail data on soil layers and monthly water composition is provided to the model. With such simple extension the SALTIRSOIL_M model provides lower leaching requirements. Therefore, similar leaching requirements, and hence, irrigation requirements, to those calculated with more complex transient-state soil salinity models.

The SALTIRSOIL_M model can be used to help develop irrigation guidelines. As such it was used for the important traditional irrigation district of *Vega Baja del Segura* (SE Spain). This is located in the lower basin of the Segura River, which lower reaches are featured by high salinity. This is therefore a salt-threatened area. According to the simulations carried out with some of the most important irrigated crops in the district, irrigation could be indefinitely go on without loss of agricultural profitability and preserving natural water quality and amount providing the following recommendations are observed: i) use of 100 hm^3 yr^{-1} of Segura River water to irrigate the 15000 ha of land in the district, i.e, an average of 670 mm yr^{-1}, ii) use of tolerant rootstocks for citrus growth, iii) replacement of surface by localized irrigation systems, iv) maintenance of the system of canals to dispose of the drainage effluents.

The data from soil water and salinity probes along with the irrigation manager or advisor experience should then be used to precisely adapt such guidelines to the plot and plant scales. Soil salinity models are, therefore, the key factor in the development of decision support systems for the sustainable use of water in irrigated areas.

4. Acknowledgment

The authors would like to acknowledge the *Ministerio de Ciencia e Innovación* from the Government of Spain for funding the projects CGL2009-14592-C02-01 and CGL2009-14592-C02-02 for the development of the SALTIRSOIL_M model. F. Visconti would also like to thank the *Conselleria d' Educació* from the *Generalitat Valenciana* for funding his work through a postdoctoral scholarship in the framework of program VAL i+d 2010.

5. References

Abadía, R.; Ortega, J.F.; Ruíz, A. & García, T. (1999). Analysis of the problems of traditional irrigation in the Vega Baja del Segura I : Current situation and considerations about its modernization. *Riegos y Drenajes XXI* Vol. 15, No.108, pp. 21-31, ISSN 0213-3660 (in Spanish)

Abdelkhaleq, R.A. & Ahmed, I.A. (2007). Rainwater harvesting in ancient civilizations in Jordan, In: *Insights into Water Management: Lessons from Water and Wastewater Technologies in Ancient Civilizations*, A.N. Angelakis, D. Koutsoyiannis (Eds.), 85-93, ISBN: 978-1-84339-610-9, Iraklio, Greece

AQUASTAT (2008). FAO's Information System on Water and Agriculture, 20.07.2011, Available from http://www.fao.org/nr/water/aquastat/main/index.stm

Ayers, R.S. & Westcot, D.W. (1985). Water quality for agriculture. FAO, Rome. 25.04.2011, Available from: http://www.fao.org/DOCREP/003/T0234E/T0234E00.HTM

Bustan, A.; Cohen, S.; De Malach, Y.; Zimmermann, P.; Golan, R.; Sagi, M. & Pasternak, D. (2005). Effects of timing and duration of brackish irrigation water on fruit yield and quality of late summer melons. *Agricultural Water Management* Vol. 74, No.2, pp. 123-134, ISSN: 0378-3774

Corwin, D.L.; Rhoades, J.D. & Simunek, J. (2007). Leaching requirement for soil salinity control: Steady-state versus transient models. *Agricultural Water Management* Vol.90, No.3, pp. 165-180, ISSN: 0378-3774

de Paz, J.M.; Visconti, F. & Rubio, J.L. (2011). Spatial evaluation of soil salinity using the WET sensor in the irrigated area of the Segura river lowland. *Journal of Plant Nutrition and Soil Science* Vol.174, No.1, pp. 103-112, ISSN 1436-8730

Goncalves, M.C.; Simunek, J.; Ramos, T.B.; Martins, J.C.; Neves, M.J. & Pires, F.P. (2006). Multicomponent solute transport in soil lysimeters irrigated with waters of different quality. *Water Resources Research* Vol.42, No.8, Article Number: W08401, ISSN: 0043-1397

Grieve, A.M.; Prior, L.D. & Bevington, K.B. (2007). Long-term effects of saline irrigation water on growth, yield, and fruit quality of Valencia orange trees. *Australian Journal of Agricultural Research* Vol.58, No.4, pp. 342-348, ISSN: 0004-9409

Hoffman, G.J. & Van Genuchten, M. Th. (1983). Soil Properties and Efficient Water Use: Water Management for Salinity Control, In: *Limitations to Efficient Water Use in Crop Production*, H.M. Taylor, W.R. Jordan & T.R. Sinclair, (Eds.), 73-85, American

Society of Agronomy, Crop Society of America, Soil Science Society of America, ISBN 0-89118-074-5, Madison, WI (USA)

Huang, Z.B.; Shan, L.; Wu, P.T. & Zhang, Z.B. (1997). Correlation between rainwater use and agriculture sustainable development of Loess Plateau of China, *Proceedings of the 8th International Conference of Rainwater Catchment Systems, Vols 1 and 2: Rainwater Catchment for Survival*, pp. 1048-1054, IDS Number: BR05T, Tehran, Iran, Apr 25-29, 1997

Ibáñez, V. & Namesny, A. (1992). Quality for irrigation of the waters of mainland Spain: I. The Segura Basin. *Tecnología del Agua* Vol.12, No.104, pp. 26-52, ISSN: 0211-8173 (in Spanish)

Isidoro, D. & Grattan, S.R. (2011). Predicting soil salinity in response to different irrigation practices, soil types and rainfall scenarios. *Irrigation Science* Vol.29, No.3, pp. 197-211, ISSN: 0342-7188

Letey, J.; Hoffman, G.J.; Hopmans, J.W.; Grattan, S.R.; Suarez, D.; Corwin, D.L.; Oster, J.D.; Wu, L. & Amrhein, C. (2011). Evaluation of soil salinity leaching requirement guidelines. *Agricultural Water Management* Vol.98, No.4, pp. 502-506, ISSN: 0378-3774

Maas, E.V., Hoffman, G.J., 1977. Crop salt tolerance—Current assessment. *Journal of Irrigation and Drainage Engineering-ASCE* Vol.103, No.IR2, pp. 115-134, ISSN: 0733-9437

MMA. (1997). Hydrological Plan of the *Segura* Basin. Confederación Hidrográfica del Segura. Ministerio de Medio Ambiente. Available from http://www.chsegura.es/chs/planificacionydma/plandecuenca/documentoscompletos/(in Spanish)

Narasimhan, T.N. (2009). Groundwater: from mystery to management. *Environmental Research Letters*, Vol. 4, No. 3, Article Number: 035002, ISSN: 1748-9326

Ramos, G. (2000). Incorporation of brackish underground water resources to water management. Southern area of Alicante province. *Industria y Minería*, Vol.339, pp. 30-35, ISSN: 1137-8042 (in Spanish)

Rhoades, J.D. (1974). Drainage for salinity control. In: *Drainage for Agriculture*, van Schilfgaarde, J. (Ed.), 433-461, Agronomy Monograph No. 17. SSSA, Madison (Wisconsin, USA),

Rhoades, J.D. & Merrill, S.D. (1976). Assessing the suitability of water for irrigation: theoretical and empirical approaches. In: *Prognosis of salinity and alkalinity* 25.04.2011 FAO, Rome, pp. 69–109. Available from: http://www.fao.org/docrep/x5870e/x5870e00.htm

Schoups, G.; Hopmans, J.W. & Tanji, K.K. (2006). Evaluation of model complexity and space–time resolution on the prediction of long-term soil salinity dynamics, western San Joaquin Valley, California. *Hydrological Processes* Vol. 20, No.13, pp. 2647-2668, ISSN: 0885-6087

Tanji, K.K. & Kielen, N.C. (2002). Agricultural drainage water management in arid and semi-arid areas. FAO, ISBN 92-5-104839-8, Rome, Italy

Turekian, K.K. (1977). The fate of metals in the oceans. *Geochimica et Cosmochimica Acta*, Vol.41, No.8, pp. 1139-1144, ISSN: 0016-7037

Visconti, F.; de Paz, J.M.; Molina, Mª J. & Sánchez, J. (2011a). Advances in validating SALTIRSOIL at plot scale: First results. *Journal of Environmental Management*, doi:10.1016/j.jenvman.2011.03.020, ISSN 0301-4797

Visconti, F., de Paz, J.M., Rubio, J.L. & Sánchez, J. (2011b). SALTIRSOIL: a simulation model for the mid to long-term prediction of soil salinity in irrigated agriculture. *Soil Use and Management*, Vol.27, No.4, pp. 523-537, ISSN 0266-0032

Visconti, F., de Paz, J.M., Rubio, J.L. & Sánchez, J. (2012). Comparison of four steady-state models of increasing complexity for assessing the leaching requirement in agricultural salt-threatened soils. *Spanish Journal of Agricultural Research* (in press), ISSN 1695-971X

Winpenny, J.T. (2003). Managing water scarcity for water security, FAO, 20.07.2011, Available from http://www.fao.org/ag/agl/aglw/webpub/scarcity.htm

Zribi, W., Faci, J.M., Aragüés, R. (2011). Mulching effects on moisture, temperature, structure and salinity of agricultural soils. *Información Técnica Económica Agraria*, Vol.107, No.2, pp. 148-162, ISSN: 1699-6887 (in Spanish with summary in English)

16

Criteria for Evaluation of Agricultural Land Suitability for Irrigation in Osijek County Croatia

Lidija Tadić
Faculty of Civil Engineering
University of J. J. Strossmayer Osijek
Croatia

1. Introduction

Considering the basic purpose of agriculture – ensuring of sufficient quantities of food with appropriate quality and unquestionable health soundness, the management of land should not sideline environmental and social aspects. Today, modern agriculture and rural development besides food production, involves ecosystems sustainability and rising values of landscape and rural space in general. Irrigation also must be part of this approach to modern food production. Irrigation in Europe is developing continuously, especially in Mediterranean countries (France, Greece, Italy, Portugal and Spain) resulting in the increase of water quantities used for irrigation. Many countries which recently joined the EU also develop their irrigation systems and this trend will probably continue. So, the future development must be done according to local natural conditions, social and economic background. As an undertaking which ensures optimal water supply for demands of agricultural production, the irrigation might have significant impacts on environment, which should be foreseen and targeted by use of economically acceptable activities in order to eliminate or lower those potentially negative impacts to the acceptable levels. The aim of every project of the hydro-melioration system, including irrigation is to ensure positive long-term effects of the implemented system which is achieved by: anticipation of potential problems, defining the means of monitoring, finding the ways to avoid or reduce problems and promotion of positive effects (Tadić, Bašić, 2007).

It can be said that importance of irrigation grows every year, even in the countries which are not located in arid or semi-arid regions. General objectives of irrigation implementation in any given area are:

- **Increasing of agricultural production and stability of production during dry years,**
- **Introduction of new more profitable crops on the market,**
- **Reduction of food import and stimulation of domestic agricultural production,**
- **Reduction of climate change impacts, first of all frequent drought periods,**
- **Reduction of agricultural land,**
- **Negative water balance during the vegetation period,**
- **Increase the interest for farming and employment in the agriculture (Romić, Marušić, 2005)**

Irrigation systems should be based upon principles of integrated water resources management and sustainable management taking under consideration potentials and restrictions of specific river basin. Several levels of data evaluation are needed:

- **Physical plans give basic information of agricultural areas, present state and future development, possible increase or decrease of the area.**
- **Soil properties are one of the most important factors because soil categorization from very suitable to not suitable for irrigation has a great impact on the final decision.**
- **Agricultural potential, mechanisation and other resources of agricultural production, including tradition of growing crops and interest of local people for irrigation. Part of the agricultural potential is developed land drainage and flood protection system.**
- **Analysis of hydrological and meteorological data, particularly analysis of drought, defines the real necessity for implementation of irrigation. Frequency, intensity and duration of water deficit in the vegetation period indicate the crop water requirement which has to be assured.**
- **Availability of water resources is one of the most restrictive criteria, where two aspects have to be considered – water quantity and quality. In the area with evident water shortage, for example Mediterranean islands, some alternative sources of water have to be applied.**
- **All possible environmental impacts of irrigation implementation should be recognized in the area due to its vulnerability and sensitivity on changes by its structure or genesis (e.g. karst regions).**

Basically, above mentioned levels of evaluation are given according to the DPSIR (driving force- pressure-state-impact-response) relationship, which is dynamic in time. Sustainability of the irrigation system can be achieved only by its constant improvement and development. Figure 1 gives a scheme of sustainable use of water resources in irrigation.

If any of the components in the DPSIR relationship changes in time, the whole scheme changes as well. The aim of sustainable approach is to achieve positive movement of the whole process, which means the decrease of pressure and unwanted impacts together with improvement of the state with ensuring domination of positive impacts. This process will be possible with strong response development.

Starting point in irrigation development is the initiative of farmers, investors and final users of the irrigation system. All other phases will be elaborated in the following chapters.

2. Physical planning

The irrigation systems are very pricey and complex undertakings and their implementation needs clear economic analysis, and no omissions should be allowed during their planning.

The initial phase in planning of irrigation systems is identification of spatial limitations as defined in physical planning documentation of either Municipality or County. Physical planning documentation, apart from natural and social characteristics of the analysed area, define the scope of economic development, including transportation, electric power, water management and other activities within the space, as well as limitations to construction in regard to protected areas.

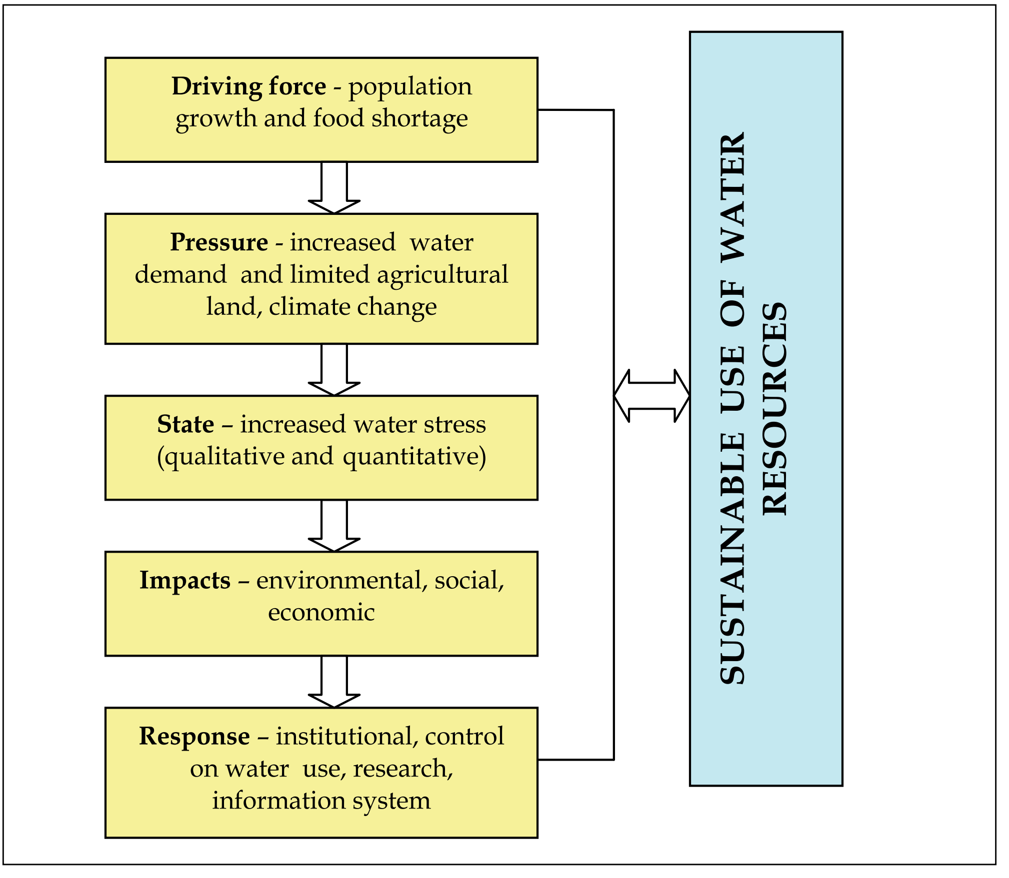


Fig. 1. Scheme of sustainable approach to irrigation (Boss, Burton 2005)

Anticipated change in landuse of a certain area, i.e. from agricultural to construction land or intersecting of the agricultural area with the large-scale infrastructure project such as road or railway, derivative channel, navigable channel or transmission line may impact a decision regarding withdrawal of construction of the irrigation system on certain agricultural land regardless of needs and natural potential.

Some of the proposed activities in space do not need to fully stop development of an irrigation system but may significantly influence the choice of irrigation methodology. These may also provoke additional costs towards implementation of environmental protection measures in the case if agricultural land is located within protected water well site or in the vicinity of areas protected for their natural values. Using physical planning documents it is possible to establish availability of water resources as well as planned activities on waterways.

For determination of agricultural land suitability for irrigation and economic feasibility of the system it is very important to consider the existing access road and electric power infrastructure, which are very important aspects for the investment project.

3. Soil suitability for irrigation

The following group of parameters which define the need for irrigation but also the its' methodology are characteristics of soil. The soil characteristics are the result of paedogenesis factors and processes, which have been influencing their mechanical, physical and chemical properties during the long period of time, and the most importantly its capability of movement and storage of water in the soil.

Along with these factors long periods of cultivation and use in intensive agriculture have contributed to significant anthropogenesis of initial natural characteristics.

Soil in this case is being analysed as a cultivation space in which during the vegetative period is lacking specific amount of water and which has to be introduced by artificial means, while getting the best possible effects:

- Maximum usage of added water which is firstly, economic but also environmental condition;
- Preservation of soil structure – during which it is necessary to assess the water regime in the soil during the entire year, especially if there is a risk of soil salinisation.

Therefore, for the assessment of soil potential for irrigation the following parameters are of key importance: soil depth, drainage and flood protection, land slope and erosion potential, water capacity, soil salinity, quantity of nutrients, etc. Based on analysis of these parameters, soli potential for irrigation is evaluated for the area of proposed activity, and also the most suitable methodology and measures required for improvement of existing soil potential are proposed.

Considering the potential for irrigation, soils are usually being classified as excellent (P-1), suitable (P-2) and restrictively suitable (P-3). In classes of potential P-2 and P-3 it is necessary to undertake hydro-technical and agro-technical interventions of different scope, which would increase the degree of their potential for irrigation (Tadić, Ožanić, et.al.2007).

This creates additional costs which investor has to bear in order to implement proposed irrigation system, but this system will then enable rational usage of water, preservation of soil characteristics and limiting of unwanted consequences to a minimum.

In specific cases, there is an occurrence of soil characteristics, which would categorise the soil as permanently inadequate for implementation of irrigation because the costs of soil characteristic's improvement would be immensely high and would impact the economic feasibility of the system, i.e. areas without surface and ground drainage, which is necessary due to retention of water in plant roots zone, or areas with a significant inclination which are prone to water erosion.

For example, Figure 2 presents total agricultural area of Osijek County, which is about 280.000 ha (100%). Part of it belongs to the Nature Park and well site for public water supply, and intensive agricultural production are not allowed (30%). Part of the area belongs to the roads, water bodies and settlements (33%), and about 1% is completely unsuitable for irrigation. The rest of the agricultural land, about 36%, can be considered as more or less suitable for irrigation according to physical and chemical properties, environmental characteristics and drainage conditions. This type of soil evaluation was made in order to avoid negative irrigation effects on the soil and to minimize the costs of land reclamation.

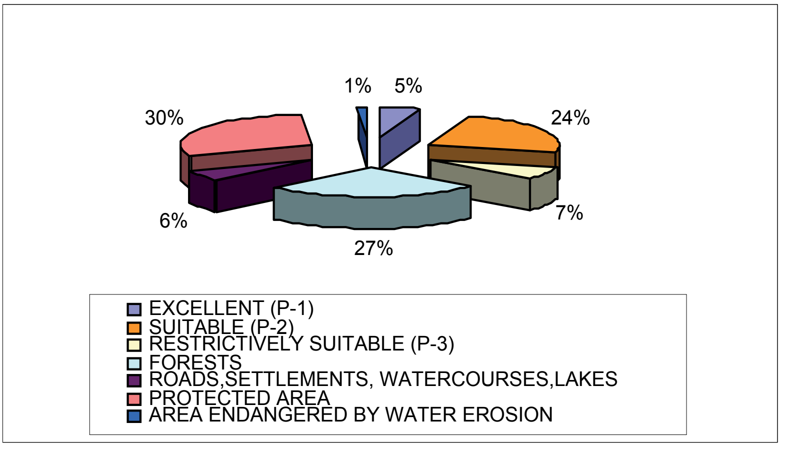


Fig. 2. Example of land suitability for irrigation in Osijek County , Croatia (Tadić, 2008)

4. Agricultural potentials

Introduction of the irrigation system implies the existence of interest of agricultural producers for improvement in production means of agricultural goods. The aim of irrigation is increase and stabilisation of yield and increase in market value of final product. Financial investments in irrigation are considerable, which means that the users should have on their disposal land, machinery, but also the knowledge which would enable them to reach the wanted goal. Existing land protection from outside waters (flood protection) and excessive surface and ground waters, and existence of the drainage system for surface and ground waters are important prerequisites for construction of an irrigation system. Agricultural potential also means readiness for introduction of new crops, which are more profitable on the market and which cultivation is impossible without irrigation.

In Croatia, majority of the continental part of the country is the traditionally agricultural area with relatively high level of agricultural production with regard to land organization, as well as production technology, mechanization and application of scientific and contemporary methods in agricultural production. Main characteristics of present crop production are as follows: orientation toward an extensive food production and small number of cultivated crops that are present on small acreage, low presence of fruit and vegetables and inadequate use of quality land resources suitable for production diversification (Tadić et al. 2007). Introduction of irrigation could enlarge the strength of present agricultural production with the introduction of more profitable, water dependent sensitive crops.

5. Irrigation necessity

The most common way of elaboration of irrigation necessity is an analysis of water deficit during the vegetation period. It causes reduced actual evapotranspiration compared to the potential evapotranspiration. Water deficit (drought) in different crop development stages causes stagnation in growth and finally reduces the yield. Drought damages depend on duration, strength and intensity of drought, which is basically characterized by geographical characteristics, soil type and sort of crop as well. In Croatia, the most severe damages are in vegetable yields, and the least in cereal yields.

During recent years many results were published, which prove damages caused by drought during the vegetation period. Table 1 presents yield reduction for crops, which are specific in Croatia.

The emphasis is given to the influence of soil type. Light soil with poor water retention capacity is more vulnerable to the water deficit.

CROP	Water deficit (mm)		Yield reduction (%)			
			Light soil		Heavy soil	
	Average year	Dry year	Average year	Dry year	Average year	Dry year
Corn	187	287	35,4	61,5	27,1	54,4
Sugar beat	246	349	36,7	58,7	29,1	52,6
Tomato	188	260	37,3	54,8	29,8	47,9
Apple without mulch	180	294	25,7	49,4	20,8	41,8

Table 1. Water deficit and yield reduction in average and dry years observed depending on soil conditions (Tadić,2008)

The fact that different crops have different sensitivity to water deficit affects the decision on irrigation implementation and cost-benefit analysis of a planned irrigation system. Intensity of crop diversification and implementation of irrigation are strongly influenced by trends on the market.

Decrease of the yields due to the water deficit can be expressed in several ways. One of them is the linear statistical relationship between total evapotranspiration and yield of cereal grains in some climate zone (Hoffman et al.2007). It can be given by equation:

$$Y_g = bET + a \tag{1}$$

where: Y_g= yield (t/ha)
ET= vegetation season evapotranspiration (mm)
b=slope of the yield-ET line (t/ha mm)
a=constant (t/ha).

The second one is very often used relation proposed by FAO (Doorenbos et al.1986):

$$\left(1-\frac{Y_a}{Y_m}\right)=k_y\left(1-\frac{ET_a}{ET_m}\right) \tag{2}$$

where: Y_a = actual harvested yield (t/ha)
Y_m= maximum harvested yield (t/ha)

k_y= yield response factor
ET_a= actual evapotanspiration (mm)
ET_m= maximum evapotranspiration (mm)

Increase in yield can be achieved by the sufficient amount of available water which will increase actual evapotranspiration in the vegetation period during crucial crop development stages.

6. Drought analysis

Draught ¸may vary in time and space, depending on climate and hydrological conditions of some area. According to World Meteorological Organization, drought is a protracted period of deficient precipitation with high impacts on agriculture and water resources. There are three types of droughts: meteorological, agricultural and hydrological drought. Any of these types can make a serious harm on agricultural production and economy in general. Long and frequent drought periods can cause desertification characterized by water shortage, overexploitation of available water resources, change and depletion of natural vegetation, reduction of crop varieties, reduction of water infiltration, etc. (EEA, 2000). Proper analysis of drought as an extreme hydrological event is essential for identification of irrigation necessity as a successful measure against it. In another hand, the same level of drought severity can cause different impacts in different regions due to the underlying vulnerabilities. Basic meteorological and hydrological data, precipitation, air temperature, evapotranspiration, relative humidity, wind, insolation and discharges must be available to provide proper analysis of drought. Figure 3 presents total annual precipitation and precipitation in growing period observed in the period from 1951 to 2000 on meteorological station Osijek, Croatia. The both trend lines show decreasing of precipitation. There is no significant decreasing during the vegetation period, which is good, but it indicates smaller possibilities of groundwater recharge during winter time.

Figure 4 presents average annual air temperature, and average air temperature during growing season observed also in the period from 1951 to 2000 on meteorological station Osijek. Increase of air temperature is obvious in both figures, but it is still lesser during the vegetation period.

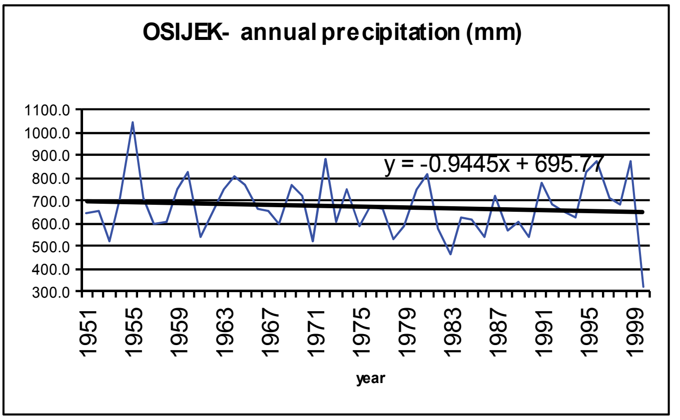
There are a lot of methods for drought estimation, developed for different climates and geographical features. Analysis of drought is very complex and the identification of a moment when drought starts and becomes extreme is very sensitive and variable.

There are two basic groups of methods: agro-climatic and hydrological. The methods in the first group are mostly based upon above mentioned two parameters, precipitation and air temperature. They give characteristics of the climate in some area with regards to the agriculture. The most common are:

- Lang's precipitation factor (KF)

$$KF = \frac{P}{T} \tag{3}$$

where: P= annual precipitation (mm) and T=average annual air temperature (^oC)



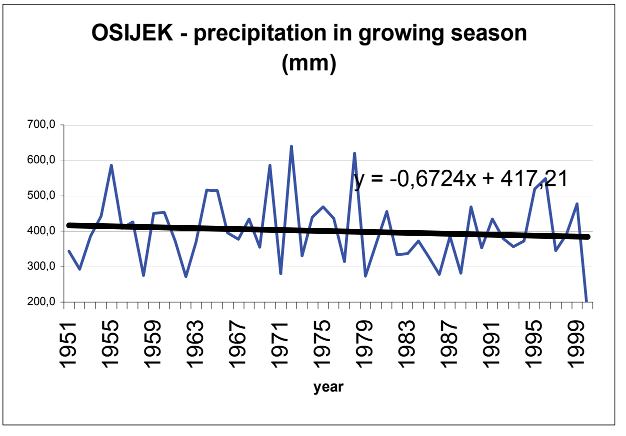


Fig. 3. Average annual precipitation and precipitation in growing season in the period 1951-2000, Osijek, Croatia

- Thronthwaite's humidity index (I_{pm})

$$I_{pm} = 1,65\left(\frac{P}{T+12,2}\right)^{10/9} \quad (4)$$

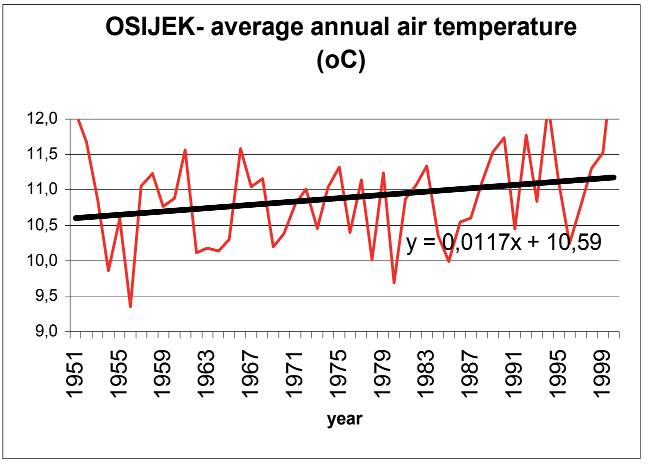
where: : P= annual precipitation (mm) and T=average annual air temperature (°C)

- de Martone's draught index (I_s)

$$I_s = \frac{P}{T+10} \quad (5)$$

where: P= annual precipitation (mm) and T=average annual air temperature (°C)

- Walter's climate diagram gives relationship between precipitation and air temperature or evapotranspiration and in that way indicates the necessity of irrigation and the length of irrigation period . According to Walter's climate diagram, irrigation is necessary only in July and August .



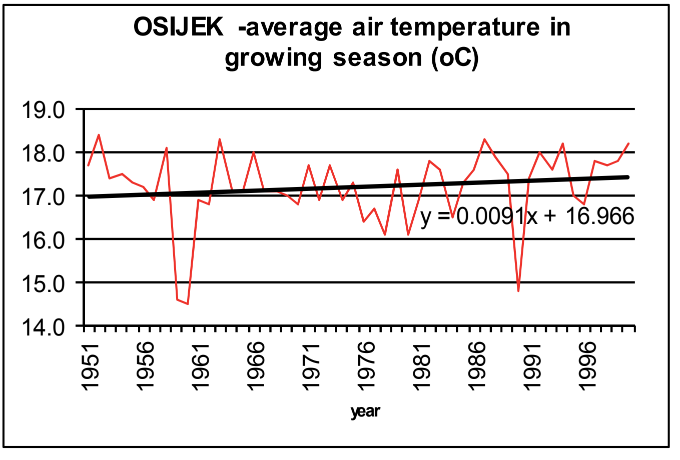


Fig. 4. Average annual air temperature and air temperature in growing season in the period 1951-2000, Osijek, Croatia

Table 2 presents climate description obtained by three of these methods applied on data of precipitation and air temperature for Osijek (1951-2000).

Lang's precipitation factor (KF)		Thronthwaite's humidity index (I_{pm})		de Martone's draught index (I_s)	
Extremes and average values	Climate description	Extremes and average values	Climate description	Extremes and average values	Climate description
KF_{min} =24,6	Arid	$I_{pm\ min}$=20,8	Semi-arid	$I_{s\ min}$=13,9	Dry sub-humid
KF_{aver}=62,2	Sub-humid	$I_{pm\ aver}$=8,1	Sub-humid	$I_{s\ aver}$=32,3	Humid
KF_{max}=98,4	Humid	$I_{pm\ max}$=75,4	Humid	$I_{s\ max}$=50,6	Per-humid

Table 2. Drought estimation obtained by Lang's precipitation factor, Thronthwaite's humidity index and de Martone's drought index

Results in Table 2 indicate climate characteristics of the region, considering annual data. They vary in the range from arid to per-humid. The average values show sub-humid to humid climate characteristics. Besides, Walter's climate diagram shows the need of irrigation in June and July what corresponds with other approaches.

The methods in the second group also use meteorological and hydrological parameters for drought identification, but they can be considered as more comprehensive and reliable.

Because of the great variety of approaches and methods, it is recommended to use more than one method to estimate an intensity of drought periods and necessity of irrigation. In that way, it is possible to give more accurate estimation of water deficit in some region. Some of the most frequently used methods will be briefly explained.

- Standard Precipitation Index (SPI) is one of the most popular methods, proposed as a most appropriate method for any time scale and any region in the world. The SPI is an index based on the probability of precipitation using the long-term precipitation record. A drought event begins when the SPI is continuously negative and ends when SPI becomes positive (WMO).

$$SPI_n = \frac{1}{\sigma_n}\left(\sum_{i=1}^{n} P_i - P_n\right) \tag{6}$$

where: n= number of monthly precipitation data,
P_i = precipitation in each month (mm),
Pn= average precipitation of the observed period (mm),
σ_n =standard deviation.

- Deciles is a method in which monthly precipitation sums from a long term record are first ranked from highest to lowest to construct a cumulative frequency distribution. The distribution is then divided into 10 parts (deciles). A longer precipitation record (30-50 years) is required for this approach.
- The Rainfall Anomaly Index (RAI) also ranks the precipitation data of the long-term period in the descending order. The average of the 10 highest values as well as that of the 10 lowest precipitation values were calculated (Figure 7).

$$RAI = \pm 3\frac{P-\overline{P}}{\overline{E}-\overline{P}} \tag{7}$$

where $\overline{P}$ is average of the annual precipitation for each year (mm) and $\overline{E}$ is average of 10-extrema for both positive and negative anomalies (mm).

- The Stochastic Component Time Series (SCTS) is given by the equation

$$Z\varepsilon = \frac{\varepsilon t-\overline{\varepsilon}}{\sigma\varepsilon} \tag{8}$$

where εt is total annual rainfall for each year (mm), $\overline{\varepsilon}$ is average annual rainfall for each year (mm) and $\sigma\varepsilon$ is standard deviation of rainfall for each year (Figure 5).

These methods applied on precipitation data observed on Osijek meteorological station (1951-2000) give results in Figure 5 and Table 3.

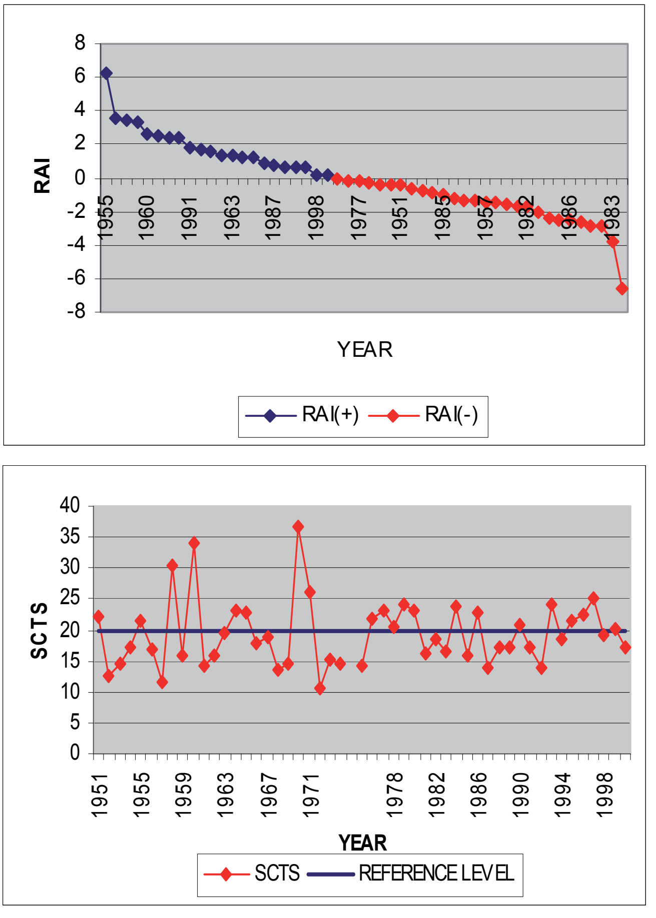


Fig. 5. Application of RAI method and SCTS method on precipitation data of Osijek, Croatia (1951-2000)

Rainfall Anomaly Index (RAI) shows that 28 years in the observed period were dry and 22 were less dry. According to Stochastic Component Time Series (SCTS) 29 years were dry and 21 years less dry.

Standard Precipitation Index (SPI)		Deciles	
Value	Classification of dryness	Months (%)	Classification dryness
-4,4	Extremely dry	23	Average
		56,5	Below the average
		20,5	Very much below the average

Table 3. Application of SPI Method on precipitation data of Osijek, Croatia (1951-2000)

Standard Precipitation Index (SPI) indicates the considered period extremely dry and Deciles classified 77% of the total number of months in the 50 years long period as below and very much below the average.

In the hydrological analysis, it is very often stressed that data series of precipitation, discharge, water level, etc., should be as long as it is possible. The length of the data series should guarantee reliability of final results and conclusions. This can be questioned due to the process present in recent decades, often referred to as a climate change. Hydrological analysis based upon a long-term data series (50, 70 or 100 years) sometimes can lead to the false conclusions. In that case, it is recommended to apply the RAPS (Rescaled Adjusted Partial Sums) method. This analysis helps us to recognize any change in time series, like periodicity, sudden leaps or smaller errors in the data series. Figure 8 and 9 present two examples of RAPS implementation. The example on Figure 6 shows annual precipitation data (1948-2008) of Vela Luka and Korčula, small places in Korčula Island in Adriatic Sea. The complete data series show the negative trend line of the same magnitude. Application of RAPS resulted by obvious break in the both data series, which occurs in 1982 and the both sub-series have the positive trend line (Ljubenkov, 2010).

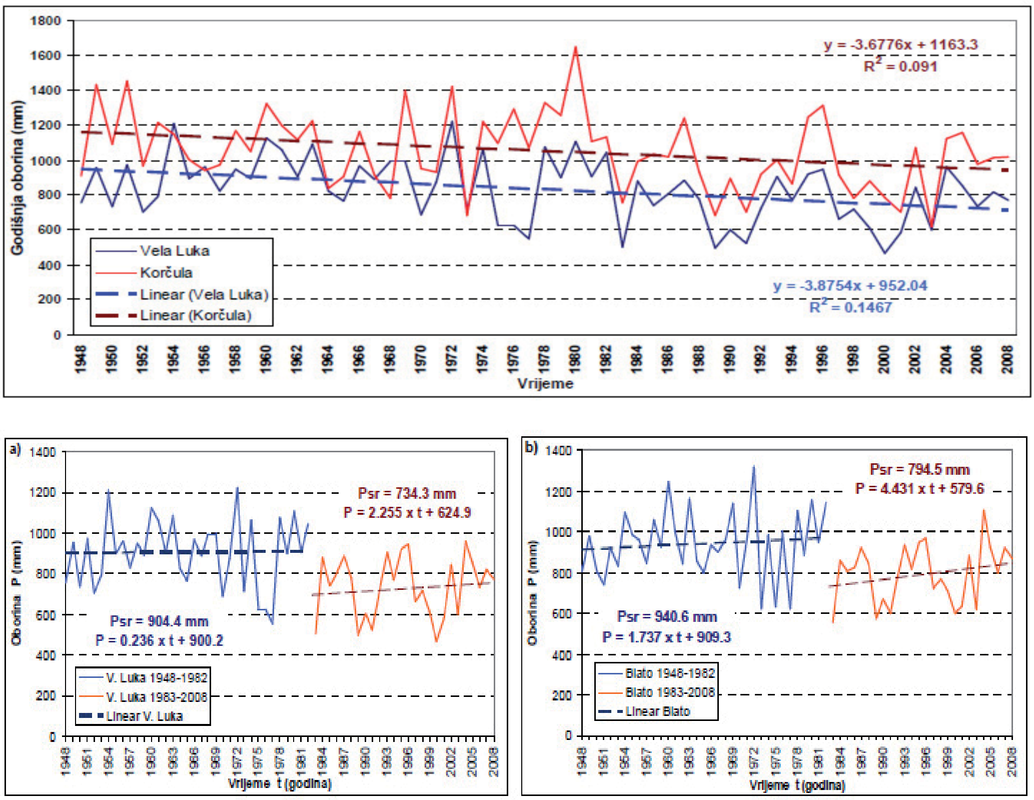


Fig. 6. Application of RAPS method on precipitation data of Korčula, Croatia (1948-2008) (Ljubenkov, 2011)

Figure 7 presents application of RAPS method on annual precipitation data of Osijek (1951-2000) and it shows two breaks, in 1974 and 1990. The first data sub-series 1951-1974 have a mild positive trend line, and next two sub-series have emphasised negative trend lines. Comparing to the complete annual data serine presented in Figure 3 with the continuous negative trend line the difference is significant.

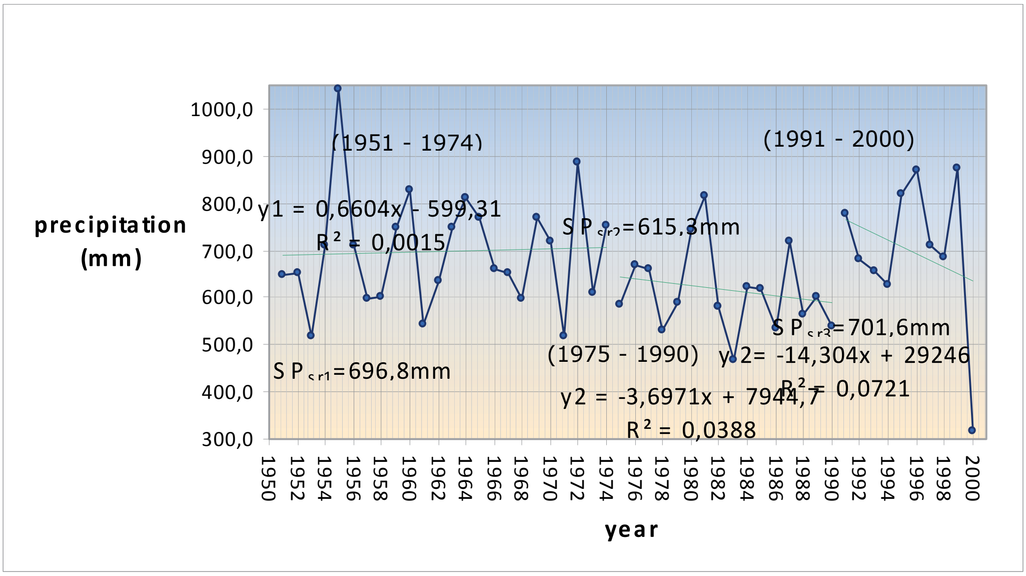


Fig. 7. Application of RAPS method on precipitation data of Osijek, Croatia (1951-2000)

7. Water availability

The next important precondition for implementation of irrigation systems is availability of water and is one of the most limiting factors. Water resources are estimated in accordance to three criteria: quantity, quality and location. Together they form water potential (Đorđević, 1990). Quantities of water required for irrigation are considerable and depend on water deficit, crops and size of the area. All three characteristics have to be met in order for water capture to satisfy long-term needs and if only one of them is not met, quantity, quality or accessibility of location such source of water becomes questionable. Usual sources of water for irrigation are rivers, ground water tables and reservoirs, and in the more recent times various non-conventional sources. In the majority of Europe and world, the shortage of water is becoming more emphasised, especially in some regions, and every new consumer of water significantly affects the water balance. Large rivers often have multiple uses: navigable waterway, electric power generation, capturing of water for different purposes, the recipient of waste waters and provision of quality water environment for a number of species, and all these requirements have to be met without conflicts in interest. About 30% of abstracted water in Europe is used for irrigation, but in some Mediterranean countries (Italy, Spain, Greece) this percentage exceeds 55-80% (Nixon et al, 2000).

7.1 Open watercourses

Favourable conditions found in open water bodies for capturing of water for irrigation depend on their hydrological regime. Waterways with the glacial hydrologic regime are more suitable, since they have maximum flows during beginning of summer (June), while waterways with the pluvial regime have minimal flows during summer months in vegetation periods. It is important not to forget the global trends in the decrease of water quantities, increase of frequency and duration of low water regimes, which also cause droughts (Bonacci, 2003). Therefore, capturing possibilities are significantly reduced at low and average water flows for purposes of irrigation during vegetation periods. The limiting factor for such waterways is maintenance of biological minimum required for sustaining of life in water. Quality of water in open waterways generally meets requirements for irrigation.

7.2 Ground water

Ground water usage in irrigation is a very sensitive, but also easily available and cheap solution. Its quality is excellent and there are no qualitative restrictions for irrigation or any other usage. In the most of the countries it is the major public water supply resource. Groundwater overexploitation can endanger capacities of public water supply systems. That is the basic reason of its protection by heavy regulations in many European countries, and in Croatia as well.

Ground water exploitation is especially sensitive in the coastal region due to the possibility of salt water intrusion in aquifers.

In some countries, like Germany, Portugal, Lithuania special permission for groundwater usage in irrigation is required, and the exploited quantities are supervised by official persons (Tadić, Marušić, 2008). In Croatia, possibilities of groundwater usage in irrigation are limited to the resources which can be renewed in the one year.

7.3 Reservoirs

The construction of reservoirs represents a very acceptable but expensive solution applicable in cases where no other sources of water are present. Since reservoirs are very expensive structures they are often constructed as multipurpose structures having to meet requirements of all users, which may lead to conflict of interest, for example, generation of electric power and usage of water for irrigation. Quality of water in the reservoir depends on its geographic location and surrounding area, but in most cases meets the required quality for irrigation.

Natural lakes can have a great potential for usage in irrigation in the quantitative and qualitative sense. However, they are very often protected due to their biological values and landscape features.

7.4 Non-conventional water resources

Use of non-conventional water resources imply the use of treated waste water, rainwater, saline water and melted snow in regions where there are no sufficient amounts of the water present. Use of these sources of water for irrigation in a safe way for agricultural land and environment altogether, is very expensive, and is made possible by intensive development of technology for water treatment. Waste water re-use and seawater desalination are increasing in Europe (e.g. Southern Europe). Application of re-used water should be subject to more research on health aspects.

In Croatia due to wealth of water resources, these forms of water capture are rare, but it is recommended to use captured rainwater on Croatian Islands (Bonacci, 2003).

8. Environmental issues

In the case where there are protected areas in the vicinity of agricultural land, implementation of irrigation should not make any negative impacts on them. All environmental impacts of irrigation should be recognized and evaluated. According to the categorisation of environmental impacts, the expected impacts, which arise due to application of irrigation are:

- According to the *type of impact* – impacts on natural assets, predominantly on water and soil (physical environment), but also on quality of life (social-economic impacts),
- According to the *duration of impact* – long term,
- According to *the occurrence in time and space* - direct, since they occur on exact area, which is being irrigated and during the period of irrigation, but also *indirect*, which means that they also impact the downstream and upstream soils, and frequently appear only after significant periods of time,
- According to the *number of impacts* - individual and cumulative (Tadić, 2009).

All those elements make the impacts very complex and hardly predictable, while the intensity of their occurrence depends on properties of the watershed, water abundance, properties of soils, quality of water being used for irrigation, as well as depending on the applied methodology and means of irrigation.

This implies that the application of irrigation may leave permanent (irreversible) consequences on the environment if the impacts are not recognised, foreseen and possibly mitigated or completely prevented. Some of the changes are easily noticed and quantified, but there is a vast number of indirect impacts that are delayed in time after the prolonged application of irrigation and often appearing outside of the irrigated area. The solutions are found in systematic planning, designing, construction and operation of undertaking. For this reason, large-scale irrigation projects should include environmental impact assessment prior to the construction which will establish the possible alteration to the environment and assess the sustainability of the system.

8.1 Impacts on water

The irrigation has quantitative and qualitative impacts on surface and ground waters.

8.1.1 Impacts on water balance

Any capture of water will impact the existing water balance. Considering the occurrence of water resources in time, every uncontrolled capture, especially in dry periods, may result in undermining of minimum biological requirements of waterways. Some watercourses have minimum flows at the time of vegetation growth when there is a need for irrigation. In smaller waterways and streams this issue is even more pronounced. Hydrologic regime of surface waters is directly related to the levels of ground waters (Romić, Marušić, 2005). During the dry periods, ground waters feed the waterways while in the period of high-water levels, surface waters feed the ground waters. Intensive capturing of surface waters combined with usually water level slope result in increased hydraulic gradient in relation to ground waters. Impacts of capturing of water above renewable limits may appear after prolonged periods of utilisation and may result in lowering of ground water levels on wider area. In coastal areas lowered levels of ground waters may cause intrusion of salt water. Continuous lowering of ground waters, along with changes in water balance, may have effect on other economic activities and water customers. Such changes have the significant impact on sensitive ecosystems, firstly, on low-lying forests and wetlands.

As it was mentioned before, one of the solutions for ensuring supply of sufficient quantities of water for irrigation is construction of water reservoirs. Such structures are considered to be very sensitive hydro-technical undertakings, especially if they are reservoirs with large volume and area, which may have significant impacts on the environment, including both positive and negative effects. With construction of reservoirs, there is a change in land-use of the area (Tadić, Marušić, 2001). The reservoirs are considered as the most controversial hydrothechnical structures which on the one side enable rational use of water collected during wet periods of the year (flood protection), and from the other side have number of environmental consequences – change of landuse, impacts on landscape and wider environment, change of hydrological and biological characteristics of a waterway. Land area is being turned over into a water surface, which changes the fundamental biological structure. Furthermore, the transition from natural to the controlled regime of a waterway after construction of the reservoir causes the number of changes. One of them is a reduction of sediment transport, which is being accumulated and deposited within the reservoir along with increased kinetic energy of water, which affects river bed and banks downstream. Reservoirs have positive effects on the regime of low and high water level periods and consequently, on replenishing of ground water resources in the downstream area.

Changes in the hydrologic regime related to capturing of water may increase concentration of water pollution and generally affect the good status of water quality. Areas exceptionally sensitive to changes in water balance are protected ecosystems whose subsistence is dependent on sufficient water quantities, water capture areas, waterways with decreasing characteristic of water flow trends and coastal areas. One of the sensitive water resources are narural lakes and use of water from natural lakes is not recommended. Some of the lakes in Croatia are already under protection, and there is an incentive to protect all natural lakes in order to preserve values of their ecosystems (Romić, Marušić, 2005).

8.1.2 Impacts on water quality

Water pollution is broad term, but it is generally defined as the reduction of quality due to introduction of impurities and potentially harmful substances. Agriculture is one of the largest non-point sources of water pollution, which is generally hard to identify, measure and monitor. The irrigation is undertaking, which impacts the changes in the water regime of soil, and consequently, on transport of potentially harmful substances to the surface and ground waters (nitrates, phosphorus) causing the eutrophication. Plant manure, residuals of pesticides and other components of agricultural chemicals in natural and irrigated conditions with changed water balance are subject to flushing from soil, and as such they represent a pollution threat to water resources. The speed and intensity of pollution transport from soil depend on a number of factors related to hydrogeological and soil characteristics of the area. In this regard, the especially sensitive are karst and alluvial areas with the relatively thin topsoil layers. Possible protection measures include:

- Adjustment of existing regulations to international standards, or regulation of issues, which are not so far covered by the laws (Ayers, Westcot, 1985)
- Setting up of monitoring system, especially in case where irrigation is present;
- Setting up of an efficient supervision system.

8.1.3 Protected areas

Significant limitations to intensification of agriculture also referring to irrigation are areas under protection. For example, protected drinking water areas in Republic of Croatia amount to 19 % of land areas, while regulations are limiting agricultural production within zones I and II of sanitary protection, with zones III and IV of sanitary protection having no limitations. Meanwhile on water protection areas there should be no priority development of irrigation projects, because of protection applied to water resources aimed at drinking water supply. However, currently there are 2200 km² of protected areas used for agricultural production, with different types and intensity of utilisation (Romić, Marušić, 2005). In the case that within protected areas, and in compliance with valid regulations, there is a justified plan for intensive use of land for agriculture and construction of the irrigation system, it is required to complete the environmental impact assessment which will provide answers if the proposed technology of agriculture may have significant negative impacts on protected component of environment or on any other component of ecosystem. Possible protection measures may include:

- Controlled capture of surface water along with preservation of biological minimum and other requirements (water supply, hydro-energy, inland navigation),
- Controlled capture of ground waters within renewable limits,
- Ensuring of biological minimum in waterways on which reservoirs are built,
- The preference is given to smaller reservoirs over bigger ones,
- Discharge of sediment from reservoirs for safeguarding equilibrium within the waterway,
- Monitoring of ground water levels on wider area of undertaking,
- Monitoring of low water flow trends.

8.1.4 Impacts on biosphere

Changes in land-use of area and changes within ecosystems for purposes of agricultural production, along with application of irrigation, have direct impacts on biosphere. Transition of non-fertile land with specific ecosystems developed (wetland, forest and meadow ecosystems with great biological diversity), which was the common practice not so long ago is now forbidden and not practised any more.

Secondary or indirect impacts on biosphere as a consequence of irrigation may appear with significant reduction of ground water levels, which impairs biological conditions within an ecosystem. According to the Croatian Law (*Law on environmental protection*, OG 82/94) the main aims of environmental protection are permanent preservation of biological diversity of natural communities and preservation of ecological stability, followed by preservation of quality of living and non-living environment and rational use of natural resources, preservation and regeneration of cultural and aesthetic values of landscape and improvement of environmental state and safeguarding better living conditions (Tadić, 2001).

9. Sustainable irrigation

Previously elaborated matter deals with the main characteristics of agricultural land, which should be analysed and evaluated in order to define land suitability for irrigation. The main objective of land evaluation for irrigated agriculture is to define actual physical needs for irrigation and to predict future conditions after development has taken place. Therefore, all relevant land characteristics, including soil, climate, topography, water resources, existing and planned agricultural production, etc. and also socio-economic conditions and infrastructure need to be considered. Some factors that affect land suitability are permanent, and others are changeable at a cost. Typical examples of almost permanent features are meteorological characteristics, basic soil characteristics, topography and landscape. Features changeable with costs are water resources, agricultural potential and soil suitability for irrigation. The costs of necessary improvements can be determined (e.g. construction of a drainage system), so the economic and environmental consequences of development can be predicted. Figure 8 gives a scheme of evaluation criteria (A) and their influence on irrigation suitability (B) in large-scale projects. The third part of the relation (C) is more related to the projects of smaller scale. Parameters of irrigation methods and performance (C) must have separated economic analysis, more detailed and adjusted to the specific project. Five groups of criteria (A) can significantly reduce total agricultural area.

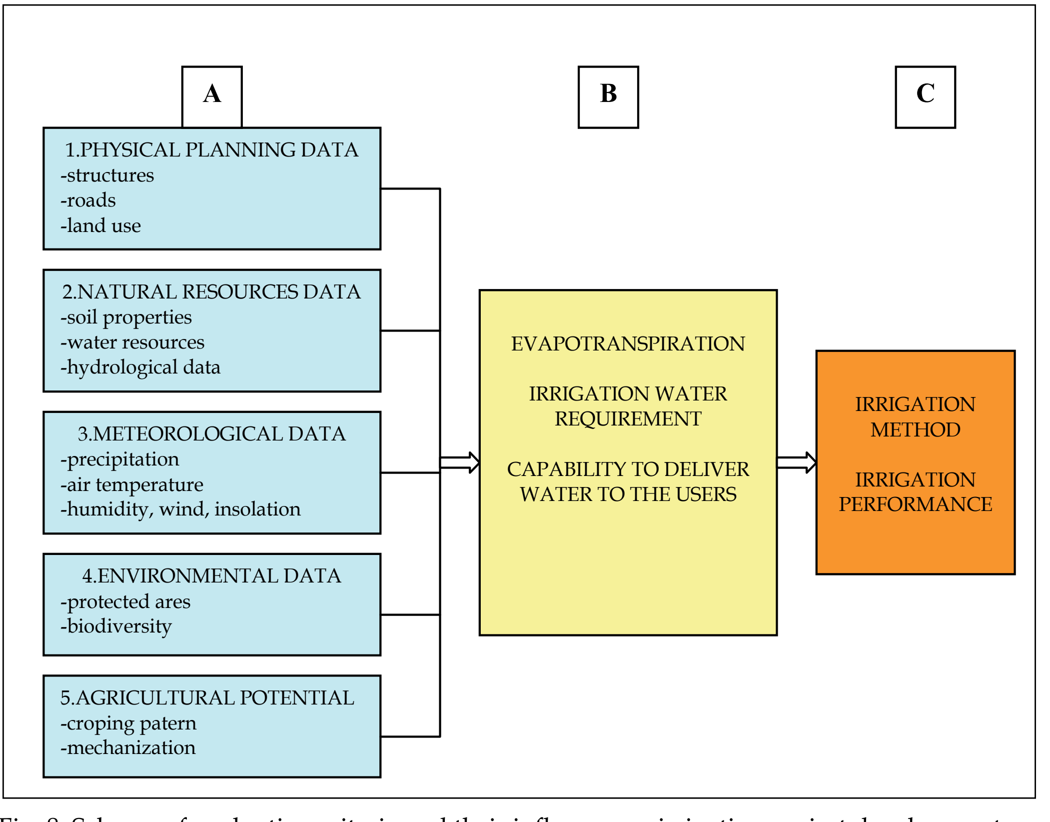


Fig. 8. Scheme of evaluation criteria and their influence on irrigation project development

According to the scheme, priorities in sustainable irrigation implementation would have already existing agricultural areas with types of soils suitable for irrigation considering their infiltration properties, areas where irrigation would not impact the overall environment. Besides, capturing of water from accessible water resources with a favourable hydrological regime must ensure sufficient amounts of water.

By meeting the required criteria, favourable conditions are accomplished for further development of a project on a lower level. Every case of neglecting of specific criteria or absence of systematic analysis leads to increase of investment value, and in long-term to overuse of natural resources and threats to the environment. On Figure 9 there is a scheme of reduction of total of agricultural land in regard to set criteria. Overall reduction may amount to over 50 %. Agricultural land found to be suitable for development of an irrigation project is subject to further economic analysis regarding application of specific irrigation methodology or choice of water sources for irrigation.

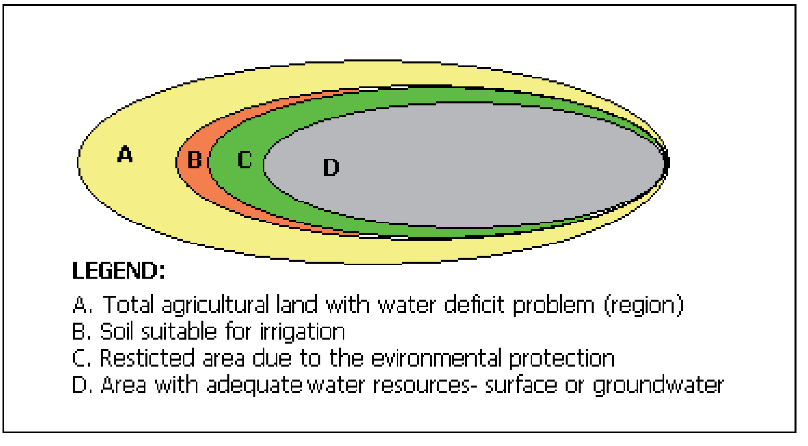


Fig. 9. Scheme possible reduction of total agricultural land in regard to irrigation suitability

Finally, the proposed procedure of data management contributes to the proper decision making. As an illustration, Figure 10 presents two maps of an agricultural land in Osijek County in Croatia (Master Irrigation Plan of Osijek County,2005). Previous analysis indicated a water deficit in vegetation period and frequent drought periods in the area.. The Figure 12a) shows the present state of irrigation, which is not very developed, basically only few separate fields have irrigated agriculture using water from open watercourses. After the process of evaluation of land suitability for irrigation, the second map (Fig. 10 b) shows agricultural areas with available water resources (open watercourses, ground water, reservoirs) on soil suitable for irrigation (excellent, suitable and restrictively suitable). All areas under any level of protection are considered to be unsuitable for irrigation development.

After this evaluation of land suitability for irrigation follows the procedure on a smaller scale by applying some of the multi-criteria methods. The most commonly used is linear programming, which is very suitable for this kind of problems. Optimal water management considers evaluation of available water resources in order to reach minimum expenses and satisfying needs of all other water users. Linear programming gives an optimum solution which can with minimum expenses of the system (structures, equipment, operation and

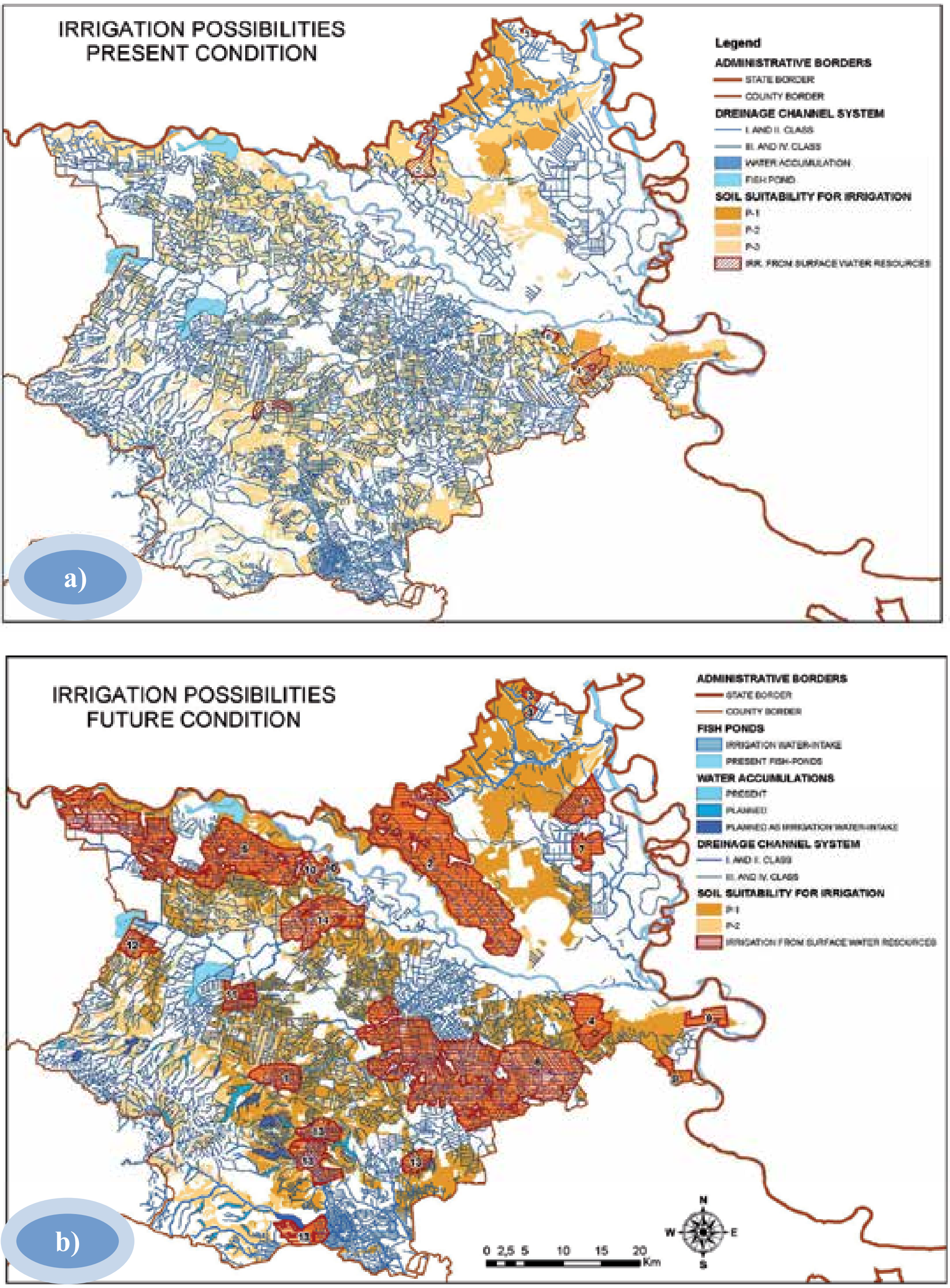


Fig. 10. Irrigation possibilities of Osijek County area, Croatia (Master Irrigation Plan of Osijek County, 2005)

maintenance) realize the maximum socio-economic benefits. Socio-economic benefits include, besides the least water price, increasing of employment possibilities, development of new economic fields, improvement of cropping pattern, etc.

10. Conclusion

To avoid subjectivity and unilaterally approach the very complex problem of irrigation implementation, methods of multi-criteria or multi-objective analysis have to be applied. This chapter tried to explain the procedure of this procedure on large-scale projects. Following of this procedure helps decision-makers to develop the project of irrigation based on sustainability and integrated water management. Considering regional physical plans, soil suitability, climatic characteristics and other geographical features, availability of water resources and their environmental vulnerability and environmental protection in general, it is possible to evaluate agricultural land suitable for irrigation. In that way, the total agricultural land will be reduced to the much smaller area, which has the good basis for irrigation implementation with reduced side effects. On a field scale, further system optimization is needed for specific cost-benefit analysis, which was not part of this elaboration.

Besides a relatively large number of potential negative side effects of irrigation described in literature and tested on the irrigated fields, without any doubts it can be said that implementation of irrigation is the necessary measure in agricultural production. The success in achieving irrigation sustainability depends on available data, reliability of the proposed procedure and reasonable data interpretation.

According to present negative trends in water and soil availability and large efforts made in environmental protection, future irrigation projects will even more depend on this kind of procedure. So we may expect development of more sophisticated and complex methods for evaluation of irrigation projects.

11. References

Ayers, R.S.,Westcot, D.W(1985). *Water Quality for Agriculture* (EDition) , FAO Irrigation and Drainage Paper 29, Rome

Bonacci, O.(2003). *Korištenje nekonvencionalnih vodnih resursa u sušnim područjima*, In: *Priručnik za hidrotehničke melioracije,* III/1, Nevenka Ožanić, 337-347, HDON, Rijeka.

Bonacci, O.(2003). *Ekohidrologija vodnih resursa i otvorenih vodotoka*, AGG Split & IGH Zagreb

Boss, M.G., Burton, M.A., Molden, D.J.(2005). *Irrigation and Drainage Performance Assessment-Practical Guidelines*, CABI Publishing, UK

Doorenbos, J.,Kassam,A.H.et.al.(1988). *Yield Response to Water* (4th E,dition) , FAO Irrigation and Drainage Paper 33, Rome

Đorđević, B.(1990). *Vodoprivredni sistemi*, Građevinski fakultet Beograd, Tehnička knjiga Beograd

Hoffman, G.J., Evans, R.G.,Jensen, M.E. et al (2007): *Design and Operation of Farm Irrigation Systems*, ASABE,

Ljubenkov, I.(2011*). Održivo gospodarenje vodnim resursima Korčule s naglaskom na njihovo korištenje za poljoprivredu*, Disertation, AGG Split, 2011.

Nixon,S.C.,Lack, T.J., HUnt,D.T.E.,Lallana,C et.al.(2000). *Sustainable use of Europe's water*. Environmetal assessment series No.7,EEA, Luxembourg

Romić, D.,Marušić,J.(2005). *Nacionalni projekt navodnjavanja i gospodarenja poljoprivrednim zemljištem i vodama u Republici Hrvatskoj (NAPNAV)*, Agronomski fakultet Zagreb.

Tadić, L., Marušić, J., Tadić, Z.(2001). *Sustainable Development of Land Management in Croatia*, 19th Regional Conference of International Commision on Irrigation and Drainage,Brno-Prag

Tadić, L (2001). *Analysis of Indicators Relevant for the Sustainable Water Management on the Karašica-Vučica Catchment Area*, Građevinski fakultet Osijek

Tadić, Z. (2005). Master Irrigation Plan of Osijek County ,hidroing Osijek

Tadić, L., Tadić, Z.,Marušić, J. (2007). *Integrated use of surface and groundwater resources in irrigation*, Proceedings of 22nd European Regional Conference ITAL-ICID, Pavia, Italy

Tadić L., Bašić F.(2007). *Utjecaj hidromelioracijskog sustava navodnjavanja na okoliš (Environmental impacts of irrigation).* Proceedings of the symposium Ameliorative measures aimed at rural space development, Croatian Academy of Sciences and Arts;173-190. Zagreb

Tadić,L.,Ožanić, N., Tadić,Z., Karleuša, B.,Đuroković, Z.,(2007). Razlike *u pristupima izradi planova navodnjavanja na području kontinentalnog i priobalnog dijela Hrvatske Hrvatske vode*, Vol.15, No. 60, 201-212, Zagreb

Tadić,L.(2008). *Example of integrated use of surface and groundwater resources in irrigation in Croatia.* Journal of Water and Land Development, No. 12, 95-112

Tadić, L., Marušić, J.(2008*). Osnovni pokazatelji o načinu uređenja, korištenja i upravljanja sustavima za navodnjavanje u dijelu država Europske unije – s razvijenim navodnjavanjem*. Unpublished study.

Tadić,L.,Tadić Z.(2009). *Impacts of Irrigation on the Environment* //18th International Symposium on Water Management and Hydraulic Engineering / Editors: Cvetanka Popovska, Milorad Jovanovski. Skopje.University St Cyril and Methodius,Faculty of Civile Engineering Skopje. 2009. 659-667

Law on environmental protection (OG 82/94)

17

Rationalisation of Established Irrigation Systems: Policy and Pitfalls

Francine Rochford
La Trobe University
Australia

1. Introduction

Global concern about food security has prompted a focus on increasing productivity using increasingly scarce resources. In Australia, as in many countries, a growing population and the projected effects of climate change and shift mean that water is the focus of much of this concern. However, as in many other established economies the infrastructure designed to move water from relatively water-abundant areas to provide irrigation is aging. It requires significant investment to guard against its failure, to ensure it meets modern standards of safety, and to ensure that water is productively used and that wastage is minimised.

In accordance with the dominant global view that prioritises free trade, to which Australia subscribes, competition policy prescribes that irrigation infrastructure is provided on a 'user pays' basis – the cost of infrastructure is factored in to the cost of the water. In northern Victorian irrigation regions, where this policy has been aggressively implemented, water costs have been 'unbundled' to reflect usage, maintenance, service and infrastructure costs, so that the usage component does not form a significant part of the total water charge. In such an environment, the major infrastructure investment needed to renew irrigation infrastructure cannot be provided directly by irrigators.

The question of investment in irrigation infrastructure is common to many developed countries. In the arid states of the United States, which followed a similar 'nation-building' path in the funding of irrigation infrastructure (Lampen, 1930; Newell, 1903) irrigation infrastructure is in poor condition (US water infrastructure needs seen as urgent, 2009). Building irrigation capacity in developing countries has been identified as a priority, and major irrigation schemes are being built in China and India. However, the optimal model of investment and ownership of infrastructure is still a matter for significant debate (Abbot and Cohen, 2009). This is of particular significance when returns on commodities are subject to market distortions, so that irrigators paying for irrigation infrastructure will be competing with irrigators who are not.

The situation in Australia is of significance to any region seeking to optimise water capture and extraction for irrigation purposes. It is not clear how the current round of irrigation industry reforms will affect the industries and communities reliant on irrigation; the context, background and effects of those reforms should be closely considered.

This chapter will critically analyse irrigation industry reforms in northern Victoria, Australia. Irrigation in this region is undergoing significant organisational and infrastructure reform. With extensive assets, increasing conveyance costs and competing demands for water, managers of irrigation businesses have implemented far-reaching changes which will have flow-on effects for irrigation customers.

The social, political and legal context of these reforms is significant, so this account will commence with consideration of the national cooperative agreement that water should be managed according to the national competition agenda, the corporatisation of water authorities, the implementation of 'user-pays' principles and unbundled water charges, and the development of trade in water. Subsequent pressures as a consequence of a major drought have brought into sharp focus the environmental impact of water extractions. Market mechanisms, along with direct government acquisition of water entitlements have been directed towards reducing the irrigation 'take' from the Murray Darling system. As a consequence, in northern Victoria, modernisation, rationalisation and reconfiguration projects have been developed. These are aimed at reducing irrigation water use and contracting the coverage of irrigation infrastructure. This chapter will consider the modernisation process in northern Victoria. It will consider the implementation of a 'backbone' set of water conveyances, selected on the basis of water usage, and 'connection' back to that conveyance of channels and 'nibs'. The processes by which the 'backbone' was identified, the impact of that decision on irrigators, and the negotiation of the 'connections' program will require consideration of the formation of irrigator syndicates, the privatisation of irrigation infrastructure, and vexed questions regarding liability for failed assets, particularly on public roads and crown land. The reality of postulated water 'savings' has become a matter for political debate, and the economic and social consequences of the modernisation project have been matters of concern.

2. Irrigation policy drivers in Australia

Irrigation policy in Australia is driven by competing environmental and agricultural water needs, the cross-party acceptance of a market driven National Competition Policy (http://ncp.ncc.gov.au/), and increasing infrastructure costs as a result of aging infrastructure and increased engineering and safety requirements. These drivers impact at different levels and to different extents, and can, as will be seen, be derailed by short-term populism.

The irrigation policy environment, particularly in Victoria, has been characterised by a series of disruptive changes since the mid-1980s. These have delivered changes in governance, a decline in water availability, the introduction of water trading, unbundling of the water 'product' and change in the nature of the water 'right' itself.

2.1 Competition policy reform

Competition policy reform is expressed in states' commitment to a national competition agenda. The competition framework was endorsed by the Council of Australian Government (CoAG), made up of the Commonwealth and State Governments. In relation to water, the CoAG, an Intergovernmental Agreement on a National Water Initiative between the Commonwealth of Australia and the Governments of New South Wales,

Policy driver	Date	Primary focus
Water (Central Management Restructuring) Act (Vic).	1984	Replacement of State Rivers and Water Supply Commission with Rural Water Commission
Water Act (Vic)	1989	Introduced water trading
		Conversion to Bulk Entitlements
Water (Rural Water Corporation) Act (Vic).	1992	Corporatisation of Victorian water authorities
CoAG National Water Initiative	1995	Market principles increasingly applied to water
Murray Darling Basin Commission Cap	1997	Diversions from the Murray Darling Basin capped at 1993-94 levels.
Essential Services Commission Act (Vic)	2001	Regulation of rural water providers through the Essential Services Commission – introduction of a process to regulate water prices on the basis of cost recovery
Water (Resource Management) Act (Vic)	2005	Unbundling of water 'product' in Goulburn-Murray Water area - existing water rights are converted into water shares, delivery rights and water-use licences; separation of water from land; creation of water share register
Water (Governance) Act (Vic)	2006	Mirroring of corporate principles in water governance
Water Act (Cth)	2007	Federalisation of water resource management; Formulation of Basin Plan

Table 1. summary of market based policy drivers

Victoria, Queensland, South Australia, the Australian Capital Territory and the Northern Territory (CoAG, 1995) operates on the premise that national productivity will be improved by the marketisation of water resources.

The adoption of market principles is broadly consistent with view across a number of developed nations that the state provision of services is marred by state failure. State-owned enterprises were targeted for reform taking a number of forms, including structural change by unbundling activities currently provided by monopoly bodies; commercialization, by requiring that an enterprise market its services on a commercial basis to achieve at least cost recovery; contracting out of functions; corporatization to establish the body on a fully commercial basis but as a state owned company, with a delineation of the roles of the Government and the entity; and privatization of the government owned business, either wholly or partly (Department of the Treasury, 1993).

In the United Kingdom privatization of water resources occurred under the Conservative Government in 1989, representing the largest and highest level of privatization in the world. Privatization has also occurred in the United States (Water Science and Technology Board, 2002). This prevalence of the view that the adoption of market principles in the provision of government services is a good thing takes in 'a number of strands of economic thinking … claims about the nature of organizational functioning and public policy-making' (Walsh, 1995: 15) and the 'ineffective' and 'inherently wasteful' institutional framework implementing state activity and policy (Walsh, 1995: 15). Pusey notes the tendency of the dominant view to 'see the world in terms that neutralize and then reduce the norms of public policy to those of private enterprise' (Pusey, 1991: 8).

In Victoria there is a continuing reluctance to privatise water itself. The potential for a political backlash if such an attempt was made was recognised by the Victorian Parliament itself, when the *Victorian Constitution* was amended to prevent privatization of Victorian water authorities. The *Constitution (Water Authorities) Act 2003* (Vic) entrenches the responsibility of public authorities to continue to deliver water by the insertion of a new Part VII in the *Constitution Act 1975* (Vic). Section 97(1) states that if at any time on or after the commencement of section 5 of the *Constitution (Water Authorities) Act 2003* a public authority has responsibility for ensuring the delivery of a water service, that or another public authority must continue to have that responsibility. However, the section does not prevent the authority from contracting with another regarding the service, whilst retaining responsibility for it, and this has been a dominant mechanism in the provision of water services in Victoria.

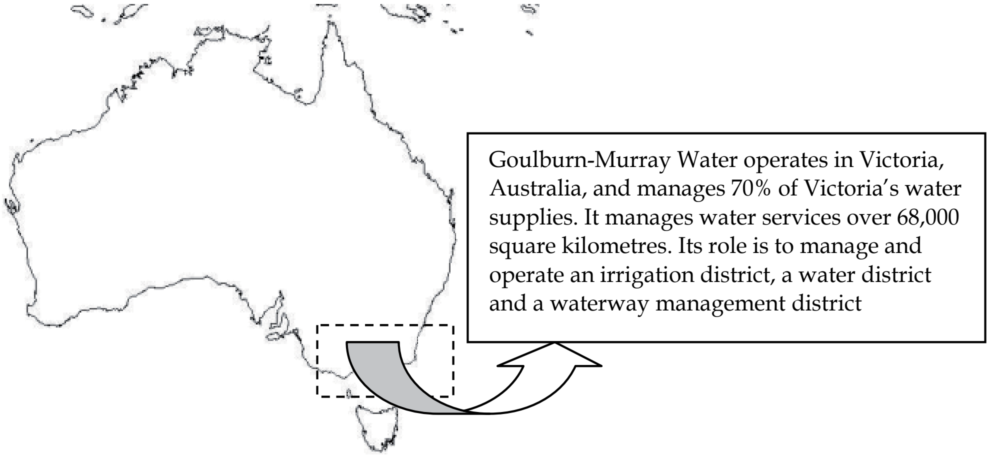


Fig. 1. Primary case study area

The situation in Victoria is a case study for the potential effects of irrigation trade in a geographically extensive, arid, aging, largely user-pays system. The area managed by Goulburn-Murray Water (http://www.g-mwater.com.au/about/regionalmap), is comprised of gravity irrigators, pumped irrigation systems, surface water diverters, groundwater irrigators, stock and domestic customers, commercial operators (such as tourism operators), and bulk water purchasers, such as urban water corporations.

The facilitation of trade in water in Victoria is a continuation of the National Competition Policy, driven by the Productivity Commission, and now overseen by the National Water Commission (the NWC), the Australian Competition and Consumer Commission (the ACCC) and the Essential Services Commission (the ESC). According to the National Water Commission, 'water trading is a centre piece of national water reform'.

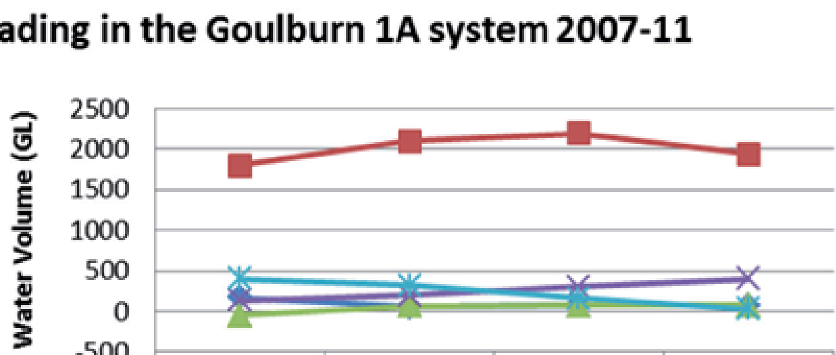
The development of a national 'grid' to enable water trade is presumed to deliver a range of benefits:

- Enhancing the capacity to 'adjust' to changing agricultural circumstances, such as low commodity prices;
- Facilitating land use changes; for instance, purchasing more water to more fully utilise land, or selling water and converting to dryland farming;
- Enabling irrigators to 'hedge' against periods of poor rainfall by selling irrigation entitlements; for instance, in a period of prolonged drought some irrigators are able to convert to non irrigation operations, or to
- Liberating the embedded capital in a farming enterprise by enabling irrigators to sell or secure against their entitlement (separately from land);
- Enabling the transfer of water to urban use, thus adding economic value to regional communities;
- Improving the efficiency of water use by enabling water delivery to reflect market costs and encourage transfer to more efficient uses.

Water trading in major irrigation regions in Victoria can occur on a permanent or a temporary basis, and sophisticated methods have been devised to facilitate its occurrence. Water brokerage firms are common, and large water suppliers have user-interface systems which allow online trading of water. For instance, Goulburn-Murray Water developed the 'Watermove' web trading interface at www.watermove.com.au. It allows trade in water allocation, water shares, groundwater, and unregulated surface water. There is no doubt that water trading has, since its inception, provided significant flexibility for irrigators. During the recent decade-long drought water trading was particularly beneficial, and analysts of the effect of water trading have used these figures to illustrate its positive effect (National Water Commission, 2010a). A clear picture of the effects of water trade in an individual irrigation area is more problematic; consolidated records provide detailed information about the amount of water traded, whether it is permanent or temporary, high security or low security water, and the regions from or into which it was traded (National Water Commission, 2010b).

An indicative comparison of water traded in the Goulburn system in the height of the recent drought (2007 – 2010 irrigation seasons) demonstrates relatively flat net volumes traded (into the irrigation district) but high total volumes traded, demonstrating that water was moving between irrigators. It is possible to interpret this as a rational response to water shortage by those able to obtain a higher price per megalitre of water by selling it than they could by utilising it - particularly since overall water allocations may have been too low to continue normal farming operations. The fluctuations in temporary price are more indicative of the yield per megalitre of water, since purchase of permanent water in a given year would not necessarily deliver a full water allocation in that year.

Positive messages about the effect of water trade as a comparison to the alternative – water attached to land and unable to be traded - display some blindness to the historical position. Because of State government policies prior to the marketisation of water, irrigators were required to pay for water regardless of whether they received it or not. This was deliberate measure to ensure the ongoing viability of the irrigation infrastructure, and a lesson learned by government by the failure of private irrigation ventures during years of drought. Prior to 1986, during years of low allocation, irrigators could receive no water, but still be required to pay for that water. Conversely, if they did not need the water, but received an allocation, they were obliged to pay for it regardless. Thus, there was no incentive to conserve water, severe impediments to changing land use, and ongoing costs in years of low income. The capacity to trade an allocation delivered immediate benefits. Irrigators whose land use was constrained by lack of water could improve the productivity of that land by purchasing additional water, and farmers who wished to transition out of farming, or transition out of irrigation farming, had additional mechanisms with which to do so.



	2007-8	2008-9	2009-10	2010-11
Permanent Volume Traded (net)	171.736	55.038	82.994	70.973
Permanent Median Price (A$)	1800	2100	2200	1940
Temporary Volume Traded	-47.129	63.626	73.922	79.247
Total Temporary Volume Traded	132.162	198.736	306.894	398.171
Temporary Median Price ($A)	401	322	165	27

Table 2. Volumes traded in the Goulburn 1A Irrigation Zone.

However, marketisation of water was accompanied by a number of other mechanisms, including the unbundling of the water product into a number of products representing separate charges for delivery, infrastructure, and water components. The actual volume of water is not a major proportion of the bill. Thus, under the provisions of the *Water (Resource Management) Act* 2005 (Vic), which amends the *Water Act* 1989 (Vic), existing water rights were converted into water shares, delivery rights and water-use licences. The irrigator is able to trade the actual water share, but the infrastructure access fee would still be payable, unless the irrigator surrenders it. In order to surrender the access fee the irrigator has to pay a termination (exit) fee, which can be prohibitively expensive (ACCC, 2009b).

The purpose of the infrastructure access charges and the termination fees is to ensure the viability of the infrastructure in the event of significant numbers of water users exiting the water district. The obvious corollary to this is that, contrary to the principle of facilitating flexibility in land and water use, holders of large delivery shares are locked into irrigation enterprises. There is the theoretical potential for people to trade the delivery share, however there is no market for that component. During the unbundling process irrigators with an existing right were given one delivery share for each hundred megalitre of water entitlement. However, the delivery share was devalued because irrigators requiring temporary water can acquire 270 megalitres on a parcel of land for each delivery share. There is, therefore, no market for the sale of delivery shares.

2.2 Environmental pressures

The environment is traditionally a matter within state Constitutional competence. State-based environmental legislation has a significant impact on the delivery of water in rural areas. Longstanding environmental measures at state level include those pursuant to the *Catchment and Land Protection Act* 1994 (Vic), the *Environment Protection Act* 1970 (Vic), the *Flora and Fauna Guarantee Act* 1988 (Vic), the *Heritage Rivers Act* 1992 (Vic) and the *Planning and Environment Act* 1987 (Vic). Environmental requirements also apply under Part 3 of the *Water Act* 1989 (Vic). Coverage by federal legislation has increased as a consequence of High Court interpretations of the external affairs power enabled by s.51(xxix) of the constitution, but significant co-operative measures had been taken to implement desirable environmental measures. In particular, the Murray Darling Basin Commission Cap was implemented to restrict diversions to 'the volume of water that would have been diverted under 1993/94 levels of Development. In unregulated rivers this Cap may be expressed as an end-of-valley flow regime' (MDBMC, 1996). The primary objectives of implementation were:

1. to maintain and, where appropriate, improve existing flow regimes in the waterways of the Murray-Darling Basin to protect and enhance the riverine environment; and
2. to achieve sustainable consumptive use by developing and managing Basin water resources to meet ecological, commercial and social needs.

As a consequence of the environmental stresses occasioned by the recent drought there has been a wholesale attempt to federalise basin-wide management of the water resource. The *Water Act* 2007 (Cth), partially based on a patchwork of constitutional powers and partially a result of negotiations between the Commonwealth and each Basin State, was realised only when a drought of over a decade duration began to threaten urban water security. However, it had as its fundamental premise the desire to manage the Basin on a global basis, and in particular to limit extractions of water, in order to 'provide for the integrated management of the Basin water resources in a way that promotes the objects of [the *Water Act* 2007 (Cth)], in particular by providing for:

a. Giving effect to relevant international agreements (to the extent to which those agreements are relevant to the use and management of the Basin water resources); and
b. The establishment and enforcement of environmentally sustainable limits on the quantities of surface water and ground water that may be taken from the Basin water resources (including by interception activities); and
c. Basin-wide environmental objectives for water-dependent ecosystems of the Murray-Darling Basin and water quality and salinity objectives; and
d. Water to reach its most productive use through the development of an efficient water trading regime across the Murray-Darling Basin; and

e. Requirements that a water resource plan for a water resrouce plan area must meet if it is to be accredited or adopted under Division 2; and
f. Improved water security for all uses [sic] of Basin water resources (*Water Act* 2007 (Cth) s.20).

The Basin Plan has not yet been released; at the time of writing it had been delayed again until October 2011 (Slattery, 2011). Significant controversy has arisen over the appropriate balance to be struck between environmental, social and economic values in devising the Plan (ABC News 2010; Stubbs, Storer, Lux and Storer 2010). Whether the environment was to have priority in the final Basin Plan was a matter of competing legal views. There was a real question as to whether the Act required the Authority to privilege the environment over other concerns (Kildea and Williams, 2011). There are significant concerns as to whether the Authority is the appropriate body to balance social and economic factors with environmental concerns. The forwarding of social objectives is more properly left to political consideration. The *Guide to the Proposed Basin Plan* (MDBA, 2010a) prioritised the environment and required significant cuts to irrigation entitlements, but the negative response to the proposed plan (Cooper 2010; Lloyd, 2010a), however, and the return of rain (Lloyd 2010b) have delayed the progress of reforms.

2.3 Regional policy

Regional policy frequently demands political responses, and the vulnerability of policy-making which affects rural communities was demonstrated by the political fallout from the *Guide to the proposed Murray-Darling Basin Plan* (MDBA, 2010a). The priority for regional policy in Australia has, however, for many years, been the facilitation of 'sustainable' or 'resilient' communities, and the 'adjustment', with government assistance, of those that appear to be unsustainable. The government or quasi-governmental agency enables the individual or community to become a self-sufficient agent. Marketisation of water infrastructure and water resources is consistent with this view, since it conceptualises the individual as capable of utilising transactional mechanisms, such as contract, to achieve optimal personal outcomes. Full cost recovery on government supplied infrastructure, such as dams and channels, is necessary to ensure that the community is 'sustainable'. Trade in water ensures that water can move from an 'unsustainable' community to a sustainable one.

Analyses of the operation of market mechanisms for water transfer have been characterised as supporting this view; the National Water Commission, in a study of the effects of water trading in the southern Murray Darling Basin, concluded that 'water markets and trading are making a major contribution to the achievement of the NWI objective of optimising the economic, social and environmental value of water. The overwhelming conclusion of the study is that water trading has significantly benefited individuals and communities across the sMDB' (NWC, 2010, v).

The interaction between regional policy and the various water policies, however, is complex, particularly where the contraction of essential infrastructure is concerned. The basis upon which infrastructure – particularly water infrastructure – is reduced has far-reaching consequences for regions, since it affects rural rate bases, school and hospital viability, and a range of other service that depend on population density. The contraction of water infrastructure in the northern Victorian irrigation regions is driven by the decision that the infrastructure is unsustainably expensive on a user-pays basis. As a generalisation this is problematic; there are elements of cross-subsidisation across irrigation districts in the larger water suppliers. Like all organisations the depreciation of infrastructure and the allocation of maintenance costs make a significant difference to whether the area is operating at a loss. Overall, the entirety of Goulburn-Murray Water is required to operate on a full-cost recovery basis (Standing Committee on Finance and Public Administration, 2007 - 2008). However, one of the consequences of modernisation of infrastructure will be an increase in the cost of that infrastructure for users on an ongoing basis.

3. Political, and environmental stressors

3.1 Water scarcity and centralisation of water policy

Thus, at the commencement of the new millennium Australian water policy was broadly consistent. However, the manner by which states implemented that policy, and the degree of compliance with key objectives, varied significantly. The more populous states of New South Wales and Victoria, with developed irrigation industries and a long history of appropriation, do not have the same interests as Queensland, with a shorter history of development and greater incentive to continue to allow diversions, or South Australia, with a capital city entirely dependent on extraction and a developing horticultural industry. Although compliance with national water policy is assessed, and Commonwealth tranche payments are dependent on that compliance, states' ability or willingness to set up the appropriate mechanisms has not always been evident. The Commonwealth suspended competition payments to SA, Victoria and NSW for not meeting their commitment to enable interstate trade in water by the agreed date of July 2006, and subsequently gained in-principle agreement to enable trade.

The decade of drought in the 1990s, however, allowed the federal government to assert significant political pressure on the states to centralise water resource management in the basin more thoroughly. Increasing pressure on urban supplies necessitated massive investments in infrastructure to ensure continuing supply of water to major population centres. The perennial state shortage of infrastructure funds for the construction of pipelines and desalination plants to augment city supplies was answered by federal government leverage of funding to obtain agreement to the referral of powers necessary to pass the federal *Water Act* 2007 (Cth). The explanatory memorandum to the Act stated that it gives effect to a number of key elements of the Commonwealth Government's $10.05 billion *National Plan for Water Security*. The Act is intended to enable water resources in the Murray-Darling Basin to be managed in the national interest, optimising environmental, economic and social outcomes.

The Act was contentious, and subject to constitutional challenge, particularly by the State of Victoria, which had initially refused to refer its powers to the Commonwealth. The Act in its final form commenced operation on 3 March 2008; however, as stated above, the Basin Plan required under the Act has not yet been finalised.

3.2 State policy and the rush for results

The availability of federal funding was a significant incentive, particularly for Victoria. However, the Victorian government would have suffered political backlash if it had simply built a pipeline from rural water supplies and purchased water to augment urban supplies. Instead, it took the opportunity afforded by a proposal by rural interests to 'save' water by improving rural infrastructure, paying for it with a combination of urban, state and federal government money, and splitting the water 'saved' between the environment, urban water consumers and rural water consumers. Problematically, however, these decisions were made under the pressure of a drought, and urban water security, particularly in the capital city of Melbourne, was threatened. Thus there was significant pressure to find water 'savings' quickly, and expedite infrastructure development.

4. The 'modernisation' of irrigation infrastructure

4.1 Water savings and trade-offs

The major support for funding of infrastructure improvements is through identification of water 'savings' that can be deployed as environmental water or 'sold' to urban use. The trade metaphor enables consistency with the market-based premise within which the industry operates. Water 'savings' are generated through the replacement of meters, installation of regulators to enable closer regulation of the channel system to prevent outfall and reduce seepage (by running the channel lower) and in some cases through the lining or piping of channels. Leaving aside the highly questionable assumption of defective Dethridge wheels inevitably measuring in favour of farmers, for which significant savings have been claimed, the most significant water savings are generated through the privatisation or retirement of irrigation infrastructure.

The technologies of performance to monitor savings have, unfortunately, been preceded by the projects they are meant to be monitoring. Thus, audit of outcomes of the rationalisation processes has been performed without baseline data and the protocols for quantification of water savings had to be developed after the actions upon which the water savings were dependent had been commenced (DSE, 2010).

An early analysis of the use of water 'savings' mechanisms over other techniques was carried out by the Productivity Commission, which noted that

> One of the purported benefits of water saving investment over market purchase is that it avoids reductions in rural water use by creating 'new' water. However, water 'savings' associated with indirect purchases can be illusory. That is, measures to reduce system losses actually divert water from other beneficial uses, elsewhere in the system, that rely on return flows (PC 2006b). For example, total channel control is a water delivery technology that uses automated control gates to reduce irrigation district outfalls and improve service quality. However, district outfalls often supply downstream water users. Transferring entitlements out of the system based on illusory water savings can therefore 'double up' losses in return flows (Productivity Commission, 2008: 78)

The Productivity Commission reviewed the operation of the NVIRP alongside other water purchase mechanisms to product environmental flows – largely tender mechanisms - in 2009. However, consistent with the Commission mandate it was predicated on the use of market mechanisms to achieve the environmental outcomes and was primarily concerned with the interaction of proposed mechanisms (NVIRP, 2009).

4.2 Contraction of irrigation infrastructure

The Northern Victorian Irrigation Renewal Project (NVIRP) is a state-owned entity; the Chief Executive Officer reports through the NVIRP Board to the Minister for Water and the Treasurer. When the modernisation process is complete the assets constructed will be transferred to Goulburn-Murray Water. The aim of the 'modernisation' project now being implemented by NVIRP is to deliver 'a more efficient and affordable irrigation delivery network that is able to deliver an improved level of water delivery service and increase on-farm productivity' (DSE, 2004). Water 'savings' to be delivered from this program have been estimated as up to 425 GL annually. Of that amount, 75 GL were intended to be diverted to Melbourne, 175 allocated to the environment and 175 to irrigators in the system (King and Tonkin, 2009). The program was to have been partially funded by Melbourne Water premised on the diversion of water to Melbourne, but this was subsequently changed (Victoria Auditor General, 2009, vii). The 'Core Principles' of NVIRP, espoused by the Food Bowl Modernisation Project Steering Committee report and endorsed by the Victorian Government on 30 November 2007, are to:

- Focus on economic development
- Strive for efficiency in both water supply and farm watering systems
- Provide different levels of service to meet the needs of different customers and customer types
- Strive for an on-demand water delivery service
- Develop system components that ensure cost and service competitiveness in water supply
- Develop policies to support and guide decisions
- Stage project delivery to match funding availability (NVIRP, (nd b)).

The majority of these principles demonstrate the

> 'post-welfarist regime of the social' in which 'performance government' displaces the collectivist ethos of welfarism. Here, various state and non-state agencies become facilitators both in optimizing individual capacities to act in an entrepreneurial *and* socially responsible way, and in the diagnosis of potential risks that threaten to disrupt the achievement of personal liberty (Higgins and Lockie, 2002, 421).

The NVIRP not only reconstructs government infrastructure (on a user-pays basis) it will facilitate on-farm irrigation works, funding them with water off-sets, to enforce efficiency gains. Irrigators will inherit a high-functionality, high-cost irrigation network, and a fully marketised water trading system will enable the transfer of water from those unable to afford the higher water costs to higher value uses – such as urban use.

The irrigation area involved in the project is around 800,000 ha and 14,000 farms (Spencer, 2010: 17), and by any measure the injection of funds into the project is significant. Around $2 billion is projected to be utilised in the project in replacement of meters, and regulators lining channels and implementation of 'total channel control' systems. 'Total Channel Control' is a Rubicon Systems product aiming for 'end-to-end irrigation canal automation technology ...[and] transforming the inefficient manually operated open canal networks into fully automated, integrated and remotely controlled systems that are achieving demonstrated new benchmark delivery efficiencies of up to 90%' (Spencer, 2010, 19). The

90% efficiency claim is substantiated by a reference to the Coleambally Irrigation district during the 2006-07 year (a drought year during which irrigators had a 10% irrigation allocation in that system) (DEWR, 2007) and refers to the claims that irrigators were allocated an extra 18% water allocation because of 'savings' from the new system; but it is not clear whether this is carryover from the previous year. It is not clear whether the 'benchmark' of 90% is an average or a measure on one channel in the system. It is being compared with the 73% *average* across irrigation systems. Losses will vary according to a range of factors including soil type, gradient, supply level and infrastructure age. Further, Coleambally was a greenfields site; the infrastructure was installed when the district was developed. Thus, it was new infrastructure, and the costs of retrofitting century-old infrastructure was not an issue.

Commentators have lauded the effects of the modernisation; the Business Development Manager of Rubicon Systems (which supplies the 'Flumegates' and 'Total Channel Control' mechanisms for the upgraded system), has reported that

> A higher level of technological investment in the modernization of large unlined, gravity fed irrigation systems in the south-eastern state of Victoria has resulted in increases in efficiency from about 70% up to about 90% - a remarkable outcome. In Victoria, the water saved is being reallocated equally between urban and industrial users, the environment and to existing farmers to improve their security of supply (Spencer, 2010: 15).

Other commentators have been less laudatory; the cost of the infrastructure program in delivering environmental and urban water far exceeds the cost of purchasing the water on the market. Some irrigators are concerned not only about the projected contraction of the irrigation system, but also about the potentially unsustainable cost of the new technology, which will be likely to have a shorter lifespan than previous low-technology solutions such as the Dethridge Wheel, and will require them to bear higher ongoing infrastructure charges.

4.2.1 The backbone

The most significant factor in generating the savings required by the Northern Victorian Irrigation Renewal Program will be the contraction of irrigation infrastructure to the 'backbone'. This is the network of channels closest to the main carrier, based on the delivery share on that particular channel. Thus, modernisation works are being carried out to service those farms on the 'backbone'.

The contraction of irrigation infrastructure to the backbone was prefaced in the Victorian White Paper:

> Rationalisation of services is primarily an issue for north-central Victoria. Goulburn-Murray Water and its water service committees realize that some parts of existing distribution systems need to be closed down. They were constructed in an era of bold development and in some places are just too spread out, as well as being on land that has turned out to be unsuited to irrigation (DSE, 2004: 82)

Rationalisation was originally a separate government program, but it appears that it has now been rolled over into the Northern Victorian Irrigation Renewal Program, resulting in difficulties ascertaining whether the objectives of either program had been met.

Rationalisation of irrigation infrastructure has not been confined to 'land that has turned out to be unsuited to irrigation.' The first irrigation district to be closed was the Campaspe Irrigation District, on excellent land and close to a natural carrier, and, ironically, flooded in early 2011 and in the following season water entitled to 100% allocation. The backbone becomes the de facto mechanism for limiting public funding of infrastructure. Those on the backbone undergo a series of consultation mechanisms to determine their current and future business needs – the farm irrigation assessment process – after which a decision is made by NVIRP as to their infrastructure requirements to meet those needs. The infrastructure will be installed and monetary compensation will be paid on the basis of assets removed. Additional programs utilising federal money and handled through the Department of Primary Industries finance on-farm efficiency works such as the installation of pipes and rises to replace flood irrigation, the piping of on-farm channels, and the laser levelling of land in return for the irrigator surrendering water. The agencies are therefore facilitating the projected business infrastructure requirements – they have taken on an enabling role, brokering deals to increase the efficiency of the irrigation operations of the farm.

4.2.2 The connection programs

The primary 'technology of agency' is the connections program, pursuant to which individuals or groups who are not on the backbone must negotiate either alone or with neighbours to connect to the backbone. NVIRP notes that

> NVIRP's Connections Program involves connecting irrigators to a modernised main system of irrigation channels or 'backbone'. The program aims to consolidate supply point connections and ensure as many customers as possible are connected directly to the backbone to access improved water delivery services.
>
> Properties are connected to the Goulburn-Murray Water channel supply system via supply point connections. Through the Connections Program, irrigators are being encouraged to upgrade their supply point connections or move supply points from secondary or spur channels to the backbone via a new connection, adopting the solution that best suits their farming operations (NVIRP, nd c).

This may mean that monetary incentives for connection are available based on water savings. Further incentives are available for on-farm efficiency works from programs like the Farm Water Program (Goulburn Broken Catchment Management Authority, 2010). NVIRP processes are mediated first by negotiation between one or a number of landowners, then by contract: a standard Rationalisation Agreement (NVIRP, nd a) forever discharges Goulburn-Murray Water and NVIRP 'from any and all claims and rights for any cost, loss, liability, damage, compensation or expense arising out of or in connection with the Rationalisation or the matters contemplated by this Agreement' (NVIRP, nd a: para 8(b)). Upon signature, the landowner accepts payment of compensation 'in full and final satisfaction of all claims…in connection with the matters contemplated by the Agreement' (NVIRP, nd a: para 7(b)).

The overall difficulty with the connections program at this stage, however, is the ongoing uncertainty for irrigators who have found themselves *off* the backbone, even though their farming enterprises are otherwise sustainable and profitable. Although the program rollout has occurred over a number of years, the lack of detail on the manner in which 'connections' to the backbone will occur has been problematic, partly because it introduces the issue of the privatisation of infrastructure, and the risks and losses associated with infrastructure.

4.2.3 Privatisation of risks and losses

The perennial debate about the efficacy of 'market' mechanisms for the delivery of public services attracts the usual criticisms of wasteful government service provision (Brody, 2005: 3). Conversely, critics of market mechanisms as primary devices for delivery of social obligations instance failures in the market due to monopolization of private providers, failure to provide adequate incentives for delivery of social obligations and rising prices after privatisation of government services. Since instances of problematic introduction of market mechanisms can be dismissed where benchmarks for successful private delivery were insufficiently defined, and since reintroduction of full government provision of many services is not on the agenda, the debate must be more strategically defined.

The connections program brings public infrastructure to a single supply point. Although details have not been finally determined, the dominant model has been that water will be metered at that point. From that point, infrastructure requirements are privatised. Ongoing maintenance of that infrastructure is the obligation of the landowner or group of landowners. Additional infrastructure, such as road culverts and bridges, were also anticipated as included in private obligations, but local councils have expressed disquiet with that arrangement, and refused to accept applications for planning approval, and it has now been indicated that water authorities will be required to maintain responsibility for these assets.

If more than one landowner requires water from that single supply point, the administration of water from that supply point is also a matter for private negotiation. These arrangements are considered to be primarily of a commercial nature; decisions will be based on the current and projected irrigation business needs. This also privatizes losses on the infrastructure below the supply point, and enables NVIRP to claim these losses as part of the program savings. The expectation appears to be that contractual mechanisms will mediate relationships between affected irrigators.

Those not on the backbone continue to meet the other infrastructure demands of the system. Thus, landholders pay delivery share on the basis that they remain connected. Further, irrigators will be constrained from 'exiting' the system without the requirement to pay an exit fee. The ACCC oversees the obligation to pay an exit fee (ACCC, 2009a). The maximum termination fee allowed by the ACCC is 10 times the total infrastructure access fee (although a common requirement to pay the current year's infrastructure access fee makes it, in reality, 11 times that fee), which equates to the amount payable per delivery share. For many irrigators of average size, this amount will be in the hundreds of thousands, and it will vary between irrigation areas because the cost of maintenance of infrastructure will vary between areas. Ironically, those areas which have been most extensively modernised and thus have the most expensive infrastructure may also have the highest ongoing costs, and thus be the least sustainable. The issue of cross-subsidisation between modernised and unmodernised areas should now be closely monitored.

The ACCC notes that this arrangement may be varied by agreement, and NVIRP has indicated publicly that irrigators will be permitted to negotiate exit fees. However, where connections programs have not commenced this has not been an option.

Currently, as the details of the connections program have not yet been finalised, many irrigators are unsure whether connection back will be a viable alternative, as it will force irrigators to bear high infrastructure and maintenance costs and to reach negotiated positions with multiple irrigators without the statutory scaffolding available to authorities.

5. Conclusions

The political arguments through which the contraction of infrastructure has been made more palatable have been arguments for 'modernisation', efficiency, and the return of water to the environment. These have been most compelling during periods of water scarcity, and have been utilised to ensure that the grave political consequences of the failure of urban infrastructure have not eventuated. The processes through which modernisation have occurred have had the effect of privatising significant portions of infrastructure and transferring risk from the state to an individual or group of individuals.

There are significant risks in forwarding this strategy for regions. The increasing costs of maintaining a water supply, along with the potential to trade water to alleviate those costs, result in more and more water leaving irrigation districts. Since land with water produces more and can support greater numbers of people, the consequence of water leaving land tends to be an overall reduction in the economic wealth of the community and a reduction in the number of people in that community.

However,

> The distribution effects of water trade depend on whether the people who sell the water stay in the region and whether they invest outside the region. The effects will also depend on whether those purchasing temporary allocations are doing so to offset their sale of entitlements, or whether those irrigators selling entitlements are different to those who are purchasing allocations.
>
> The overall trend across GMW's main irrigation districts was a decline in the number of people employed in Agriculture, Forestry and Fishing … by 5% between 1996 - 2001. (DSE, 2008).

The decline in rural populations is frequently considered to be an inevitable consequence of the economic conditions in first world countries, and concerns about food security (for instance, O'Grady 2011; Schmidhuber and Tubiello, 2007; Brown and Funk 2008), are alleviated by the argument that modern farming conditions, being more efficient, require fewer participants (c/f Altieri and Rosset, 2002). However, the consequence of the contraction of irrigation is an exacerbation of loss of population by a loss of infrastructure. This is a removal of both the industry and the capacity for the industry to continue.

6. Acknowledgements

Figures in Table 2 are compiled from the Department of Sustainability and Environment, Victorian Water Register website at http://waterregister.vic.gov.au/Public/Reports/WaterAllocation.aspx

7. References

ABC News (2010) 'Report says irrigation cuts to slash jobs', 6 August [Online] Available: <www.abc.net.au/news/stories/2010/08/06/2975836/htm> [2010, August 9]

Abbot, M., Cohen, B., (2009) 'Productivity and efficiency in the water industry'. 17 *Utilities Policy* 233-244

Altieri, M.A. and Rosset, P., (2002) 'Why biotechnology will not ensure food security, protect the environment, or reduce poverty in the developing world' in Sherlock, R. and Morrey D.J. *Ethical issues in biotechnology* 175 – 182

Australian Competition and Consumer Commission (ACCC), (2009a) *Permanently selling your water and terminating your delivery right – a guide for irrigators about the water market rules and rules on termination fees*.

Australian Competition and Consumer Commission (ACCC), (2009b) *Water charge (termination fees) rules: technical guide for operators* June.

Brody, G., (2005) 'Executive Summary', in Consumer Law Centre Victoria and Environment Victoria, *Water: Access, Affordability and Sustainability: Issues Paper* May

Brown, M.E. and Funk C.C., (2008) 'Food security under climate change' 319 *Science* 580 – 581

CoAG, (1995). Intergovernmental Agreement on a National Water Initiative between the Commonwealth of Australia and the Governments of New South Wales, Victoria, Queensland, South Australia, the Australian Capital Territory and the Northern Territory, at http://www.coag.gov.au/meetings/250604/index.htm#water_initiative

Cooper, H., (2010) 'Murray–Darling plan gets fiery reception,' *Lateline Australian Broadcasting Corporation,* 14 October www.abc.net.au/lateline/content/2010/s3038842.htm (accessed November 17, 2010).

Department of Environment and Water Resources (DEWR), (2007), *Innovation in Irrigation – case studies from across Australia* http://www.nht.gov.au/publications/case-studies/irrigation2007/pubs/irrigation2007.pdf

Department of Sustainability and Environment (DSE), (2004), *Our Water Our Future: Securing our water future together*, State of Victoria, White Paper

Department of Sustainability and Environment (DSE), (2008), Water Trading in Northern Victoria 1991/92 - 2005/06

Department of Sustainability and Environment (DSE), (2010), 'Water savings protocol: technical manual for the quantification of water savings' Version 3 August

Goulburn Broken Catchment Management Authority, (2010), 'Farm Water Program' http://www.gbcma.vic.gov.au/default.asp?ID=farm_water

Higgins, V., Lockie, S., (2002), 'Re-discovering the social: neo-liberalism and hybrid practices of governing in rural natural resource management' 18 *Journal of Rural Studies* 419-428

King, A.J., and Tonkin, Z., (2009), 'Northern Victoria Irrigation Renewal Project: Operational impact assessment on aquatic fauna', Unpublished client report, Arthur Rylah Institute for Environmental Research. Department of Sustainability and Environment, Heidelberg available at http://nvirp.spyro.ddsn.net/downloads/Planning/PER/App_11._NVIRP_Assessment_of_aquatic_species.pdf.

Lampen, D., (1930) *Economic and Social Aspects of Federal Reclamation* Baltimore: The Johns Hopkins Press

Matthews, K., (2008), Chair and Chief Executive Officer, National Water Commission, *Australian Water Markets Report 2007- 2008*, December, National Water Commission, Canberra,

Kildea, P., and Williams, G., (2011), 'Professors Paul Kildea and George Williams, Gilbert and Tobin Centre of Public Law, UNSW' *Submissions received by the Committee,* 12 January 2011. http://www.aph.gov.au/senate/committee/rat_ctte/mdb/submissions.htm (accessed April 26, 2011).

Lloyd, G., (2010a), 'Great dividing rage over water' *The Australian,* 23 October. <www.theaustralian.com.au/news/opinion/great-dividing-rage-over-water/story-e6frg6zo-1225942074914> (accessed November 17, 2010).

Lloyd, G., (2010b), 'The drought breaks' *The Australian,* 13 November. www.theaustralian.com.au/national-affairs/the-drought-breaks/story-fn59niix-1225952583089 (accessed November 13, 2010).

Murray–Darling Basin Authority (MDBA), (2010a), *Guide to the Proposed Basin Plan* [Online] Available: http://thebasinplan.mdba.gov.au/guide/

Murray-Darling Basin Ministerial Council, (1996), *Setting the Cap – Report of the Independent Audit Group* November

National Water Commission (NWC), (2010a), *The impacts of water trading in the southern Murray–Darling Basin: an economic, social and environmental assessment*, NWC, Canberra

National Water Commission (NWC), (2010b), *Australian Water Markets Report 2009-2010* available at http://www.nwc.gov.au/www/html/2971-water-markets-report---december-2010.asp?intSiteID=1

Newell, F.H., (1903) 'The Reclamation of the West' *Annual Report of the Smithsonian Institution*

NVIRP, (2009), Submission to the Productivity Commission Review of Market Mechanisms for Recovering Water in the Murray-Darling Basin 8 September 2009 available at http://www.pc.gov.au/__data/assets/pdf_file/0009/91494/sub038.pdf

NVIRP (nd a), 'Rationalisation Agreement', available at http://www.nvirp.com.au/downloads/Connections/Connections_Program/Sample_Legal_Agreement.pdf

NVIRP (nd b) 'Vision and principles' http://www.nvirp.com.au/about/vision_principles.aspx

NVIRP (nd c) http://www.nvirp.com.au/connections/connections_program.aspx

Office of State Owned Enterprises, Department of the Treasury, (1993), *Reforming Victoria's Water Industry: A Competitive Future*

O'Grady, S., (2011), 'The coming hunger: Record food prices put world 'in danger', says UN' *The Independent* 6 January [online] http://www.independent.co.uk/news/world/politics/the-coming-hunger-record-food-prices-put-world-in-danger-says-un-2177220.html [accessed January 6, 2011]

Michael Pusey, (1991), *Economic Rationalism in Canberra: A Nation-Building State Changes its Mind* Sydney: University of New South Wales

Murray-Darling Basin Authority, (MDBA), (2010), *Guide to the proposed Basin Plan.* Canberra: Commonwealth of Australia

National Water Commission, (2010), *The impacts of water trading in the southern Murray–Darling Basin: an economic, social and environmental assessment*, NWC, Canberra

Productivity Commission, (2008). *Towards Urban Water Reform: A Discussion Paper.*

Productivity Commission Research Paper, Melbourne, March

Schmidhuber J., Tubiello, F.N., (2007) 'Global food security under climate change' vol. 104 no. 50 PNAS 19703–19708

Slattery, C., (2011), 'Draft Murray Darling plan delayed' *ABC News* [online] August 3

Spencer, G., (2010) 'Making large gravity irrigation systems perform' in CA Brebbia, AM Marinov and H Bjornlund (eds) *Sustainable Irrigation Management, Technologies and Policies III* 134 WIT Transactions on Ecology and the Environment 15

Standing Committee on Finance and Public Administration, (2008), *Report on Goulburn-Murray Water's Performance 2007-8*

Stubbs J., Storer J., Lux C. and Storer T., (2010) *Exploring the Relationship Between Community Resilience and Irrigated Agriculture in the MDB: Social and Economic Impacts of Reduced Irrigation Water,* report (Stubbs Report), 4 July [Online] Available: <www.cotton.crc.org.au/content/General/Research/Projects/3_03_05.aspx> [2010, August 9]

Turnbull, M. (2006), 'Malcolm Turnbull Speaks to the National Press Club in Adelaide' (Speech to the National Press Club, Adelaide, 22 November 2006) (<http://parlinfo.aph.gov.au/parlInfo/download/media/pressrel/4VLL6/upload_binary/4vll63.pdf;fileType%3Dapplication%2Fpdf> at 10 August 2011 (copy on file with author).

'US water infrastructure needs seen as urgent' (2009) *Reuters* [online] May 8, available at http://www.reuters.com/article/idUSTRE5473IG20090508?loomia_ow=t0:s0:a49:g43:r1:c1.000000:b30495740:z0, 17 June 2010.

Victorian Auditor General, (2009), *Water Entities – Results of the 2008-09 Audit* November 2009

Walsley, J., Argent, N., Rolley, F., Tonts, M., (2006), 'Inland Australia' (Paper presented at *Australians on the Move: Internal Migration in Australia*, the 2006 Annual Symposium of the Academy of Social Sciences in Australia, Australian National University, Canberra, 20–22 November 2006). Abstract avail <http://www.assa.edu.au/Conferences/details/symp2006.htm> at 27 November 2006 (copy on file with author).

Walsh, K., (1995), *Public Services and Market Mechanisms: Competition, Contracting and the New Public Management* Palgrave Macmillan

Water Science and Technology Board, (2002) *Privatization of Water Services in the United States: An Assessment of Issues and Experience*

Part 4

Strategies for Irrigation Water Supply and Conservation

18

Optimal Design or Rehabilitation of an Irrigation Project's Pipe Network

Milan Cisty
Slovak University of Technology Bratislava
Slovak Republic

1. Introduction

This chapter deals with the optimal design of the hydraulic part of an irrigation project. It is mainly focused on the design or management of the sprinkler irrigation method.

A typical sprinkler irrigation system usually consists of the following components:

- Source of the water (reservoir, river, well, waste water)
- Conduit to irrigation area (for instance, a canal or pipe system)
- Pump unit
- Pipe network (mainline and submainlines)
- Sprinklers or various types of irrigators (center pivot sprinkler system, linear move system, traveling big gun system, portable hand-move lateral pipe system, solid-set irrigation system, etc.)

This chapter deals with the optimal design of the most expensive part of a pressurised irrigation system, i.e., its pipe network. The problem of calculating the optimal pipe size diameters of an irrigation network has attracted the attention of many researchers and designers. During the process of designing an irrigation pipe network, the hydraulic engineer will face the problem of determining the diameters of the pipes forming the distribution network. For economic reasons, the pipe diameter should be as small as possible; on the other hand, the diameter must be large enough to ensure service pressure at the feed points (Labye et al., 1988; Lammadalena and Sagardoy, 2000).

Many optimization models based on linear programming (LP), non-linear programming (NLP) and dynamic programming (DP) techniques are available in the literature. Among them Labye's method is especially well known in the design of irrigation systems (Labye, 1966, 1981). This approach initially assigns the minimum possible diameter to each link without infringing on the maximum velocity restriction. From this initial situation, it is based on the concept of economic slope β_s, which is defined as the quotient between the cost increase (P_{s+1} - P_s) produced when the diameter of the link is increased and the consequent gain in head loss (J_s – J_{s+1}). The economic slope enables the characteristic curve of each sub-network to be established. Each increase in diameter is decided while trying to minimize the associated cost increase in an iterative process that ends when all the pressure heads in the network coincide with the design head.

The linear programming method is also still accepted as an approach for the optimal selection of the diameters of pipes in branched irrigation networks. Mathematical models based on LP were initially developed and used in the irrigation network design process in the former Czechoslovakia in the early 1960s (Zdražil, 1965).

Various methods for optimizing branched irrigation networks - Labye's method, the linear programming method and a simplified nonlinear method - were compared in (Theocharis, et al., 2010).

The above-mentioned methodologies are suitable only for networks without loops, which are typical in the irrigation industry. However, there are frequent situations where the presence of loops in the network is useful, e.g., when redundant parallel pipes in the network's supply are needed or the interconnection of branches to correct shortages or equalize pressure solves some design problems. A possible approach for increasing the hydraulic capacity of branch systems in the rehabilitation process is to convert them to looped networks (thereby providing alternative pathways) and increase their hydraulic capacity with a minimum capital investment. In the majority of cases the requirement to increase the hydraulic capacity of the system could be based on the following requirements, e.g.:

- To increase pressure and water demands at hydrants due to upgrading the irrigators (with increased pressure and demand characteristics).
- To provide sufficient pressure within the pipeline system with an increased number of demand points as well as grouping them in selected parts of the irrigation system.
- To expand the system by adding new branches.
- To eliminate a system's deficiencies due to its aging.

The methodologies for optimizing looped water distribution systems (WDS) mainly evolved for drinking water distribution systems, but, with some modifications, they are also applied in the irrigation industry. Alperovits and Shamir (Alperovits & Shamir, 1977) extended the basic LP procedure to looped networks. Kessler and Shamir (Kessler & Shamir, 1989) used the linear programming gradient method as an extension of this method. It consists of two stages: an LP problem is solved for a given flow distribution, and then a search is conducted in the space of the flow variables. Later, Fujiwara and Khang (1990) used a two-phase decomposition method extending that of Alperovits and Shamir to non-linear modelling. Also, Eiger, et al. (1994) used the same formulation as Kessler and Shamir, which leads to a determination of the lengths of one or more segments in each link with discrete diameters. Nevertheless, these methods fail to resolve the problems of large looped systems.

Researchers have focused on stochastic or so-called heuristic optimization methods since the early 1990s. Simpson and his co-workers (1994) used basic genetic algorithms (GA). The simple GA was then improved by Dandy, et al. (1996) using the concept of the variable power scaling of the fitness function, an adjacency mutation operator, and gray codes. Savic and Walters (1997) also used a simple GA in conjunction with an EPANET network solver.

Other heuristic techniques have also been applied to the optimization of a looped water distribution system, such as simulated annealing (Loganathan, et al, 1995; Cunha and Sousa, 2001); an ant colony optimization algorithm (Maier, et al., 2003); a shuffled frog leaping algorithm (Eusuff & Lansey, 2003) and a harmony search (Geem, 2002), to name a few.

The impetus for this work is that significant differences from the known global optimums are referred to even for single objective tasks and simple benchmark networks, while existing algorithms are applied. Reca, et al. (2008) evaluated the performance of several meta-heuristic techniques - genetic algorithms, simulated annealing, tabu search and iterated local search. He compared these techniques by applying them to medium-sized benchmark networks. For the Hanoi network (which is a well-known benchmark often used in the optimization community), after ten different runs with five heuristic search techniques he obtained results which varied in a range from 6,173,421 to 6,352,526. These results differ by 1.5 – 4.5 % from the known global optimum for this task (6,081,128), which is a relatively large deviation for such a small network (it consists of 34 pipes). Similar results were presented by Zecchin, et al. (2007) and Cisty, et al. (1999).

The main concern of this paper is to propose a method which is more dependable and converges more closely to a global optimum than existing algorithms do. The paper proposes a new multiphase methodology for solving the optimal design of a water distribution system, based on a combination of differential evolution (DE) and particle swarm optimization (PSO) called DEPSO (Zhang & Xie, 2003). DEPSO has a consistently impressive performance in solving many real-world optimization problems (Xu, et al., 2007; Moore & Venayagamoorthy, 2006; Luitel & Venayagamoorthy, 2008; Xu, et al., 2010). As will be explained in the following text, the search process in PSO is based on social and cognitive components. The entire swarm tries to follow the global best solution, thus improving its own position. But for the particular particle that is the global best solution, the new velocity depends solely on the weighted old velocity. DEPSO adds the DE operator to the PSO procedure in order to add diversity to the PSO, thus keeping the particles from falling into a local minimum.

The second base improvement proposed, which should determine the effectiveness of the proposed methodology, is the application of a multi-step procedure together with the mentioned DEPSO methodology. The multi-step optimization procedure means that the optimization is accomplished in two or more phases (optimization runs) and that in each further run, the optimization problem comes with a reduced search space. This reduction of the search space is based on an assumption of the significant similarity between the flows in the sub-optimal solutions and the flows in the global optimal solution. The details are described later in this paper.

This chapter is structured as follows: In the "Methodology" section, WDS optimization is explained and formally defined. This section subsequently describes PSO, DE, and DEPSO, together with DEPSO's multi-phase application to WDS optimal design. The experimental data, design, and results are presented and discussed in the "Application and Results" section. The "Conclusion" section describes the main achievements.

2. Methodology

2.1 Optimal design of a water distribution network

Given a water network comprised of n nodes and l sizable components (pipes, valves, pumps and tanks), the general least-cost optimisation problem may be stated mathematically in terms of the various design variables x, nodal demands d, and nodal pressure heads h. Here x is a vector of the selected characteristic values (or physical dimensions) for the l sizable system components; d is a vector of length n specifying the demand flow rates at each node, and h is a vector of length n, whose entries are the pressure head values for the n nodes in the system (note that the head depends on x and d). Here x may include, for example, the diameter of the pipes, the capacity of the pumps, valve types and settings, and the tank volume, diameter and base elevation (Rossman, 2000). In our work the least cost optimal design problem is solved, and the decision variables are the diameters of the pipelines, which must be selected from a discrete set of commercially available pipe diameters.

The design constraints are typically determined by the minimal pressure head requirements at each demand node and the physical laws governing the flow dynamics. The objective is to minimize the cost function $f(h, d, x)$. This cost function may include installation costs, material costs, and the present value of the running costs and/or maintenance costs for a potential system over its entire lifetime. For optimisation methods that cannot explicitly accommodate constraints, it is a common practice to add a penalty term to the cost function, in order to penalize any constraint violations (such as deviation from the system's pressure requirements) (Lansey, 2000). This technique requires a penalty factor to scale the constraint violations to the same magnitude as the costs.

The WDS design optimization problem is therefore to

minimize

$$f\,(h, d, x),$$

subject to

$$g\,(\mathbf{q}, \mathbf{d}, \mathbf{x}) = 0,$$

$$e\,(\mathbf{h}, \mathbf{d}, \mathbf{x}) = 0,$$

$$h_{min} \le h(\mathbf{d}, \mathbf{x}) \le h_{max},$$

$$j_{min} \le j(x) \le j_{max} \qquad (1)$$

where a set of at least n conservation of mass constraints $g(q, d, x) = 0$ includes the conservation of the flow equation for each of the nodes in the system, incorporating the nodal water demands d and the flows q for all the pipes branching from a node; the system of equations $e(q, d, x) = 0$ are energy equation constraints, specifying that energy is conserved around each loop, which then follows the pressure head constraints. The design constraints of the form $j_{min} < j(x) < j_{max}$ on the variables $j(x)$ specify the physical limitations or characteristic value sets from which the components may be selected (Lansey, 2000). These constraints may represent restrictions on discrete variables such as pipes which come in a range of commercial diameters.

The main design constraints (pressure head requirements) in the present work were determined by the EPANET 2 (Rossman, 2000) simulation model. For the purpose of the optimal design the model is first set up by incorporating all the options for the individual network components. The DEPSO then generates trial solutions, each of which is evaluated by simulating its hydraulic performance. Any hydraulic infeasibility, for example, failure to reach a specified minimum pressure at any demand point, is noted, and a penalty cost is calculated. The operational (e.g. energy) costs can also be calculated at this point if required. The penalty costs are then combined with the predicted capital and operational costs to obtain an overall measure of the quality of the trial solution. From this quality measure the fitness of the trial solution is derived. The process will continue for many thousands of iterations, and a population of good feasible solutions will evolve.

2.2 Particle swarm optimization

Particle swarm optimization (PSO) is a meta-heuristic method inspired by the flocking behaviour of animals and insect swarms. Kennedy and Eberhart (Kennedy et al., 2001) proposed the original PSO in 1995; since then it has steadily gained popularity. In PSO an individual solution in a population is treated as a particle flying through the search space, each of which is associated with a current velocity and memory of its previous best position, a knowledge of the global best position and, in some cases, a local best position within some neighbourhood - defined either in terms of the distance in decision/objective space or by some neighbourhood topology. The particles are initialized with a random velocity at a random starting position.

These components are represented in terms of the two best locations during the evolution process: one is the particle's own previous best position, recorded as vector *pi*, according to the calculated fitness value, which is measured in terms of the clustering validity indices in the context of the clustering, and the other is the best position in the entire swarm, represented as p_g. Also, p_g can be replaced with a local best solution obtained within a certain local topological neighbourhood. The corresponding canonical PSO velocity and position equations at iteration *t* are written as

$$v_i(t) = w.v_i(t\text{-}1)+c_1.\varphi_1.(p_i - z_i(t-1)) + c_2.\varphi_2.(p_g - z_g(t-1)) \quad (2)$$

$$z_i^t(t) = z_i\ (t\text{-}1)+v_i\,(t) \quad (3)$$

where w is the inertial weight; c_1 and c_2 are the acceleration constants, and φ_1 and φ_2 are uniform random functions in the range of [0,1]. Parameters c_1 and c_2 are known as the cognitive and social components, respectively, and are used to adjust the velocity of a particle towards p_i and p_g.

PSO requires four user-dependent parameters, but accompanied by some useful rules. The inertia weight w is designed as a trade off between the global and local searches. The greater values of w facilitate global exploration, while the lower values encourage a local search. Parameter w can be a fixed to some certain value or can vary with a random component, such as:

$$w = w_{max} - \varphi_3/2, \quad (4)$$

where φ_3 is a uniform random function in the range of [0,1] and w_{max} is a constant. As an example, if w_{max} is set as 1, Eq. 4 makes w vary between 0.5 and 1, with a mean of 0.75. During the evolutionary procedure, the velocity for each particle is restricted to a limit w_{max}, as in velocity initialization. When the velocity exceeds w_{max}, it is reassigned to w_{max}. If w_{max} is too small, the particles may become trapped in the local optima, where if w_{max} is too large, the particles may miss some good solutions. Parameter w_{max} is usually set to around 10 - 20% of the dynamic range of the variable on each dimension (Kennedy et al., 2001).

Izquierdo et al. (2008) applied PSO to the water distribution system design optimization problem in his work. They developed an adaptation of the original algorithm, whereby the solution collisions (a problem that occurs frequently in PSO) are checked using several of the fittest particles, and any colliding solutions are randomly regenerated with a new position and velocity. This adaptation greatly improves the population diversity and global convergence characteristics. Finally, they adapted the algorithm to accommodate discrete variables by discretizing the velocities in order to create discrete step trajectories for these variables. Izquierdo et al. tested their algorithm on the NYTUN and HANOI WDS benchmarks and achieved large computational savings (an order of magnitude better than the previous methods), whilst closely approximating the known global optimum solutions.

2.3 Differential evolution

In 1997 Storn and Price (1997) first proposed differential evolution (DE), as a generic metaheuristic for the optimization of nonlinear and non-differentiable continuous space functions; it has proven to be very robust and competitive with respect to other evolutionary algorithms. At the heart of its success lies a very simple differential operator, whereby a trial solution vector is generated by mutating a random target vector by some multiple of the difference vector between two other random population members. For the three distinct random indices *i*, *j* and *k*, this has the form:

$$y_i = x_i + \hat{f} \times (x_j - x_k), \tag{5}$$

where x_i is the target vector; y_i is the trial vector; and $\hat{f}$ is a constant factor in the range [0, 2] which controls the amplification of any differential variation, typically taken as 0.5. If the trial vector has a better objective function value, then it replaces its parent vector. Storn and Price also included a crossover operator between the trial vector and the target vector in order to improve convergence.

2.4 Hybrid DEPSO methodology

The DEPSO algorithm involves a two-step process. In the first step, the original PSO as previously described is applied. In the second step, the DE mutation operator is applied to the particles. The crossover rate for this study is given as one (Zhang & Xie, 2003). Therefore, for every odd iteration, the original PSO algorithm is carried out, while for every even iteration, the DEPSO algorithm is carried out. The procedure for the implementation of DEPSO is summarized in the following steps:

1. Initialize a population of particles with random positions and velocities. Set the values of the user-dependent parameters.
2. For every odd iteration, carry out the canonical PSO operation on each individual member of the population.

a. Calculate the fitness function $Fit(z_i)$ for each particle z_i;

b. Compare the fitness value of each particle $Fit(z_i)$ with $Fit(p_i)$. If the current value is better, reset both *Fit(pi)* and p_i to the current value and location;

c. Compare the fitness value of each particle $Fit(z_i)$ with $Fit(p_g)$. If the current value is better, reset $Fit(p_g)$ and p_g to the current value and location;

d. Update the velocity and position of the particles based on Eqs. 6 and 7.
3. For every even iteration, carry out the following steps:
a. For every particle z_i with its personal best p_i, randomly select four particles, z_a, z_b, z_c, and z_d, that are different from z_i and calculate Δ_1 and Δ_2 as,

$$\Delta_1 = p_a - p_b \,,\ a \neq b, \tag{6}$$

$$\Delta_2 = p_c - p_d \,,\ c \neq d, \tag{7}$$

where p_a, p_b, p_c, and p_d are the corresponding best solutions of the four selected particles.

b. Calculate the mutation value δ_i by Eq. 8 and create the offspring o_{ij} by Eq.9,

$$\delta_i = (\Delta_1 + \Delta_2)/\ 2\,, \tag{8}$$

$$o_{ij}= p_{ij}+ \delta_{ij},\ \text{if}\ \varphi \leq p_r\ \text{or}\ j = r \tag{9}$$

where j corresponds to the dimension of the individual, and r is a random integer within 1 and the dimension of the problem space.

c. Once the new population of offspring is created using steps a) and b), their fitness is evaluated against that of the parent. The one with the higher fitness is selected to participate in the next generation.
d. Recalculate the p_g and p_i of the new population.
4. Repeat steps 2) to 3) until a stopping criterion is met, which usually occurs upon reaching the maximum number of iterations or discovering high-quality solutions.

2.5 Multi-step approach to WDS design

The proposed approach to the WDS optimization methodology involves refining the optimization calculations in a multiple-step approach, where the search space from the first optimization run is reduced for the second optimization run. In every run the DEPSO methodology is applied. The size of the search space depends on the number of possible diameters for each link from which the optimal option could be selected. In the first phase for all the links, all the available diameters are usually considered. In this case the size of the search space is n^l, where n is the number of possible diameters and l is the number of links. In the second phase the size of the search space is $n_1.n_2.n_3 ...n_l$, where n_i is the number of possible diameters for link i, which is a smaller number than in the first phase if some of the n_i are less than n.

On the basis of the flows computed in the pipes of the suboptimal solution in the first phase, it is possible, with the help of the known design minimum and maximum flow velocities, to calculate the maximal and minimal pipeline diameter considered for a given link of the WDS network. The prerequisite for undertaking such a step is the ability of modern heuristic algorithms to approximate the global optimum with a sufficient degree of accuracy, which could now, after two decades of their development, be expected. It is therefore assumed that the resulting suboptimal solution already has flows sufficiently close to the flows in the global optimum design of the WDS. This assumption is empirically verified by the author in this paper, but it also has a logical basis, since it is known that for a given distribution of the flows in a water distribution network, multiple solutions for the design of the diameters (the main design parameter in our definition of WDS optimization) could be found to comply with the technical requirements of the system.

One of the diameter designs for flow distribution in a network is best with regard to the cost of the network. This means that there are fewer variations in the flows than there are variations of the possible diameters, so if the diameters proposed by the heuristic search engine (e.g. DEPSO) differ from the optimal diameters searched for, the flows could be quite close to them, especially when a suboptimal solution close enough to the global optimal one is considered. There is some degree of intuition in this theorem, but the proposed idea was tested with positive results (as will be referred to hereinafter). The subsequent task is to find the corresponding optimal diameters for this distribution of the flows.

A reduction of the search space is accomplished for the second optimisation run with the assistance of the minimum and maximum pipeline flow velocities allowed. These parameters allow for the calculation of the anticipated minimum and maximum diameter for every network segment. These two values set an upper and lower boundary to the new range of acceptable diameters for each pipe segment, from which the algorithm will choose the optimal values in the second run. With the above-mentioned reduction of possible particle values a smaller search space is obtained, and better search results can be expected.

3. Application and results

The Tomasovo irrigation network was used as a case study in this work. Its layout is shown in Figure 1. This is one of the irrigation facilities in Slovakia which has medium-size area coverage, and the sprinkler type of irrigation is applied. Its construction was completed at the beginning of the 1960s; the whole facility is therefore approaching the end of its service life and can be selected as a suitable model for testing the proposed optimization methods which could also be easily applied for the rehabilitation of the hydraulic system.

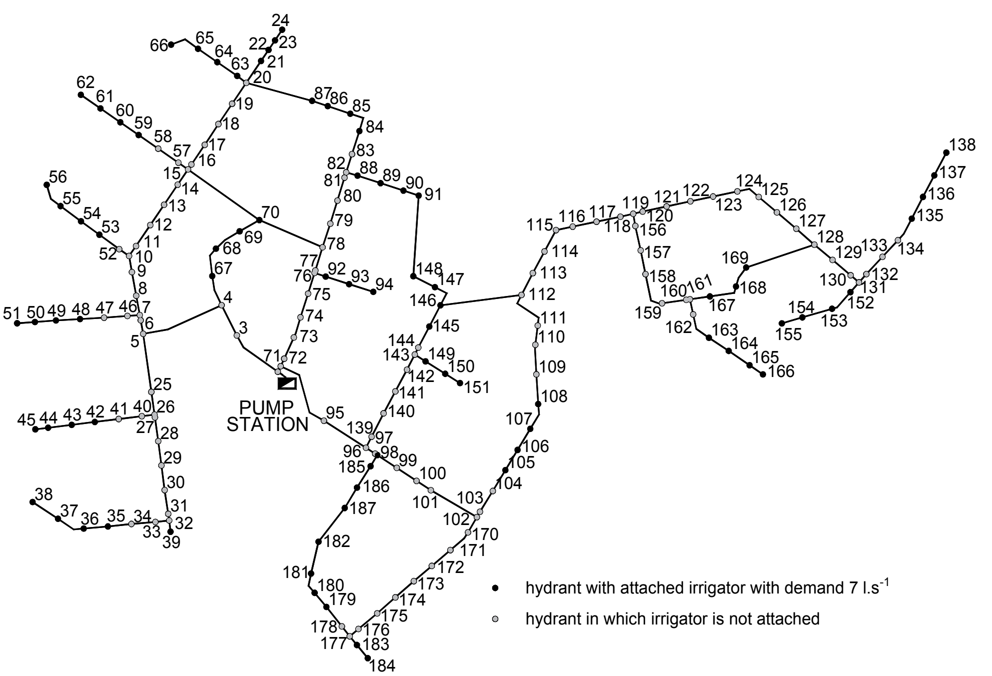


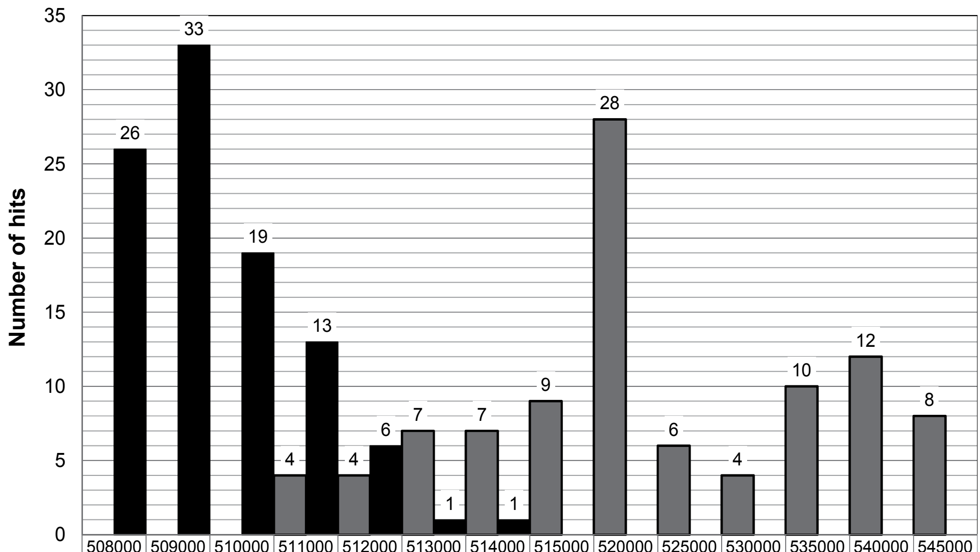
Fig. 1. Tomasovo irrigation system layout with positions of demands marked

The irrigated area of this system amounts to 700 ha. The hydraulic part of the irrigation system consists of the irrigation water take-off structure from the canal, a pump station, a pressurized network for the delivery of irrigation water, and sprinklers. For the purpose of this study it is necessary to describe only the pipeline network in detail (which is available from the author of this chapter in the form of an EPANET input file). The pump station and sprinklers represent the boundary conditions for the system analysed. Only their basic parameters (the pressure and output flow of the pump station, the required sprinkler pressure and demand flow) are taken into account in the optimization computations. A concept of irrigation with hose-reel irrigators with an optimum demand flow of 7.0 $l.s^{-1}$ and an optimal inlet pressure of 0.55 MPa is proposed for this system. In addition, it is assumed that a battery of such sprinklers will be used, i.e., there will be a set of four machines which operate as a whole on the adjacent hydrants – this approach has some advantages while managing the system, and similar operational rules could also be defined in other systems. Water is supplied through a pump station with an output pressure of 0.85 MPa and a flow of 392 $l.s^{-1}$. This means that 56 irrigators with a demand flow of 7.0 $l.s^{-1}$ could simultaneously work on the network (14 groups of irrigators). These irrigators could be placed in various hydrants of the network during the operation of this system. The worst case for their placement should be used for the design of the diameters. In Figure 1 the placement of the irrigators is displayed, the positions of which were used in searching for the optimal pipe diameters in this study. In some of the nodes the input of the water to the network is imitated in the EPANET inputs with the aim of reducing the overall flow to the maximal possible flow from the pump station and concurrently having in each part of the network such a flow which could be expected in this place during the system's operation.

This network has a total of 186 nodes supplied by one source node (the pump station). There are 193 pipes arranged in 7 loops, which are to be designed using a set of 7 asbestos cement pipes with diameters of 100, 150, 200, 300, 350, 400 and 500 mm and an absolute roughness coefficient of k = 0.05 mm. When searching for the optimal diameters for this system, a total enumeration of all possible alternatives from which the optimal solution should be chosen is not possible. The amount of possible combinations could be evaluated from a number of the above-mentioned proposed diameters powered on a number of pipes - it reaches the impressive amount of 7^{193}, which is a number with 163 digits before the decimal point. That is why the optimization methodologies described in the methodology part were applied for solving this task. The Darcy–Weisbach equation has been adapted to calculate the head losses, using EPANET 2 (Rossman, 2000). The minimum required pressure head in this network is 0.55 MPa for each demand node (which the proposed hose-reel sprinkler needs for its operation).

The computational experiments were accomplished in the following manner: Firstly, 100 testing runs of the first phase of the proposed algorithm (without reducing the search space) were computed for the Tomasovo network; the results are summarised in Figure 2. In this stage various DEPSO settings were used (DE factor=0.3÷0.8, CR=0.5÷1.0, PSO C1=C2=0.5÷1.5; $N_{population}$=100÷250 and $N_{generation}$= 500÷1000). The histogram in Figure 2 shows that the minimal (best) obtained cost of the optimized network in this phase was 510,469.5 €; the maximal (worst) network price was 544,464.8 €; and the most frequently obtained result was 515,000 € – 525,000 €. The original search space was reduced by the procedure explained in section 2.5 from the original 7^{193} to a value of 7^{100} on the basis of the flows in the most frequently obtained result (or average result) from this interval (the cost of this solution was 521,536.9 €). The mentioned one hundred runs of the first phase of the algorithm were performed with the intention of verifying the probability of obtaining this result (a reduction of the search space to approximately 7^{100} alternatives), which is a prerequisite for the next computational phase, e.g., this amount of the computations was accomplished only for testing purposes. In actual computations this is not necessary: five to ten runs would be enough, and the best solution in a real case could be taken as the basis for reducing the search space.

Thus in our testing computations, the reduced search space with an average reduction (which is also the most likely result obtained according to Figure 2) was chosen and entered into the second optimization run. The leading factor determining the search space reduction and affecting the accuracy of the calculations are, in addition, the mentioned result of the computations from the first phase of the algorithm and also the minimum and maximum flow velocities mentioned in section 2.5. The values of the velocity for the search reduction were 0.1 m.s^{-1} (v_{min}) and 3 m.s^{-1} (v_{max}). One hundred runs of the second phase were conducted similarly as in the case of the first phase computations in order to verify the probability of obtaining the final result, which is also reported in Figure 2. It is possible to see there that almost all the results from the second phase are on the left side of the results from the first phase, i.e., they are better. This means that it is better to apply our proposed two-phase algorithm than to refine or accomplish more computations without a reduction of the search space as is usual. The minimal (best) obtained cost of the optimized network in this final phase was 507,148.3 €; the maximal (worst) network cost was 513,462.0 €; and the average result was 508,970.5 €.



	508000	509000	510000	511000	512000	513000	514000	515000	520000	525000	530000	535000	540000	545000
1st phase				4	4	7	7	9	28	6	4	10	12	8
2nd phase	26	33	19	13	6	1	1							

Cost of the network [€]

Fig. 2. Histogram of first and the second phases of the optimization computations

This procedure works fully automatically and does not need an expert's assistance in the optimization calculations. The EPANET input file of this water distribution network and all the results of the computations are not presented here in the table form in detail, because an inappropriately large space would be needed for such a presentation and is available from the author of this chapter.

3.1 A Comparison of the branched and looped alternatives of the irrigation network design

Irrigation systems were usually designed with branch layout. Because we proposed in this study procedure for design of the looped irrigation networks in this chapter are optimal designs for this two possibilities evaluated. The looped layout of the tested irrigation network is reduced to branch one by removing pipes between nodes 15-70, 20-87, 70-78, 91-148, 112-146, 128-169, 182-187. The linear programming (LP) method is accepted as an approach for the optimal selection of the diameters for pipes in branched networks. For the clarity purposes we briefly describe the optimisation procedure of the pipeline network rehabilitation using linear programming. The mathematical formulation of this problem is as follows:

$$A_{11}x_1 + A_{12}x_2 + ...+ A_{1n}x_n = B_1$$

$$A_{21}x_1 + A_{22}x_2 + ...+ A_{2n}x_n = B_2$$

etc.

$$A_{m1}x_1 + A_{m2}x_2 + ...+ A_{mn}x_n = B_m \tag{10}$$

$$c_1x_1 + c_2x_2 + ...+ c_3x_n = \min \tag{11}$$

Solution has to comply with inequalities:

$$x_1 > 0; x_2 > 0 \text{ etc. up to } x_n > 0 \tag{12}$$

When in order to resolve pipeline networks optimization task linear programming is applied, unknown are the lengths of individual pipeline diameters. In conditions (10) should be mathematically expressed the requirement that the sum of unknown lengths of individual diameters in each section has to be equal to its total length. The second type of the equation in constraints (10) represents the request that the total pressure losses in a hydraulic path between the pump station and critical node (the end of the pipeline, extreme elevation inside the network) should be equal or less than the known value. This constraint is based on the maximum network pressure requirement needed for the operation of the system. Given the investment costs minimisation requirement, the objective function (11) sums the products of individual pipeline prices and their required lengths. Four possible diameters (base of v_{min} a v_{max}) are selected for each section. Further details on LP optimisation can be found in available literature, e.g., Cisty et al., (1999). The results of optimal design of the branch network by LP is summarised in the Table 1.

The results obtained indicate that the optimal design of a branched network using linear programming provides better results from an investment cost point of view (504,574.5 €)

than the calculations using DEPSO on a looped network (507,148.3 €). This follows from the fact that LP is a deterministic algorithm, which provides a real global minimum of the problem, which was defined by equations (10, 11, 12). The DEPSO method is a heuristic algorithm, which can provide results closer to a global minimum. The main reason is, of course, that there are fewer pipes in the branched alternative than in looped one. Considering the operation of an irrigation network, there are some advantages in using a looped layout, which is illustrated by evaluating the set of the real operation situations of the Tomasovo irrigation network both with branched and looped optimal designs.

The pressure assessment of the pipeline network was done in such a way that a set of realistic operational situations was analysed. These demand situations are proposed to have maximum hydraulic requirements (compatible with those used for the design of the network), and 320 various possibilities with different placements of the irrigators on the network were generated and evaluated. The next step was to run a simulation calculation of the branched and looped network configurations for all of these operational situations. In these alternatives we have assessed the minimal, maximal and average pressures at all the demand points. These values are shown in the diagram (Figure 3), where the data is sorted according to size.

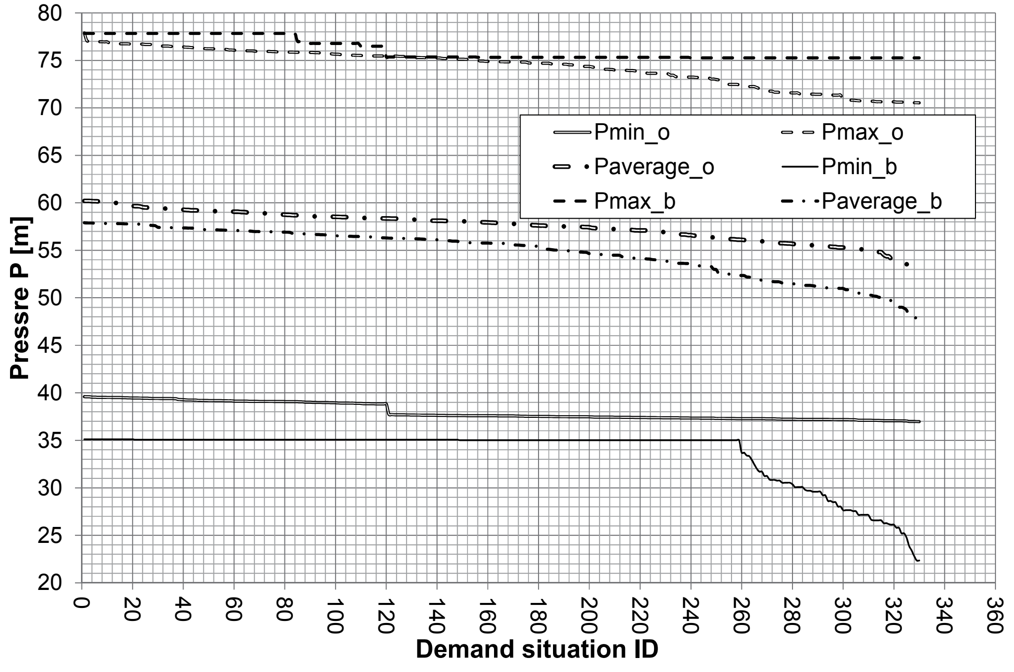


Fig. 3. Comparision of the pressures in 320 demand situations in the branched and looped alternatives

The simulation results prove the benefit of looping in hydraulic terms (better pressure ratios, lower maximal pressures, higher minimal pressures) and in economic terms – looped network rehabilitation is not much more expensive than a branched solution. There are unacceptably low pressures in branch networks in approximately 25% of the demand situations investigated, which is why a looped network should be preferred to a branched one from an operational point of view. One can assume that the results described are also applicable when designing other systems.

		Branch network		Looped network first phase		Looped network second phase	
Diameter	unit cost	length	cost	length	cost	length	cost
mm	€/m	m	€	m	€	m	€
100	15.5	5,049.6	78,268.8	8,679.7	134,535.35	8,582.2	133,024.1
150	20	7,509.8	150,196	5,671.1	113,422	6,302	126,040
200	12	6,629.8	79,557.6	8,523.9	102,286.8	8,273.7	99,284.4
300	36.5	3,756.4	137,108.6	3,194.7	116,606.55	3,015.5	110,065.7
350	47	1,171	55,037	834.3	39,212.1	730.3	34,324.1
400	55	35.3	1,941.5	35.3	1,941.5	35.3	1,941.5
500	72.5	34	2,465	34	2,465	34	2465
SUM		24,185.9	504,574.5	26,973	510,469.3	26,973	507,144.3

Table 1. Costs of the optimal design from linear programming and the first and second phase of the DEPSO algorithm

4. Conclusion

In this study the application of the DEPSO optimization algorithm for the design of a pressurised irrigation water distribution network is proposed. Its effectiveness is determined by the proposed multiple-step approach with application of the DEPSO heuristic methodology, where the optimized problem with a reduced search space is entered into each subsequent run. This reduction was obtained with the help of the assumption of a significant closeness between cost flows in the suboptimal and global optimal solutions. This assumption was empirically verified at the large Tomasovo irrigation network where this methodology was applied. The calculation results for this network show the better performance of the proposed methodology compared to the traditional, one-step application of the various heuristic methods. The benefit of designing the looped alternative versus the branch one is demonstrated by comparing the operational flexibility of networks designed by DEPSO and by linear programming.

The focus of the work was aimed at simplifying the calculations for practical use. The proposed optimization procedure could work fully automatically and does not need an expert's assistance in the optimization calculations (e.g., for choosing the various parameters of the heuristic methodology). Various improvements are possible in future research, e.g., the direct inclusion of the operation evaluation into the optimization procedure by applying a multi-objective approach.

5. Acknowledgment

This work was supported by the Slovak Research and Development Agency under Contract No. LPP-0319-09, and by the Scientific Grant Agency of the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences, Grant No. 1/1044/11.

6. References

Alperovits, E. & Shamir U. (1977). Design of optimal water distribution systems. *Water Resource Research,* Vol. 13, No.6, pp. 885-900

Cisty, M., Savic, D.A., Walters, G.A. (1999). Rehabilitation of pressurized pipe networks using genetic algorithms. *Proceedings Water for Agriculture in the Next Millennium. 17th Congress on Irrigation and Drainage*, International Commission on Irrigation and Drainage, Granada, pp. 13-27.

Cunha, M.C. & Sousa, J. (2001). Hydraulic infrastructures design using simulated annealing. *Journal of Infrastructure Systems*, ASCE, Vol.7, No.1, pp. 32-39

Dandy, G.C., Simpson, A.R. & Murphy, L.J. (1996). An Improved Genetic Algorithm for Pipe Network Optimization. *Water Resources Research*, Vol.32, No.2, pp. 449-458

Eiger, G. , Shamir, U. & Ben-Tal, A. (1994). Optimal design of water distribution networks. *Water Resources Research*, Vol.30, No.9, pp. 2637-2646

Eusuff, M.M. & Lansey, K.E. (2003). Optimization of water distribution network design using the shuffled frog leaping algorithm. *Journal of Water Resources Planning and Management ASCE*, Vol.129, No.3, pp. 210-225

Fujiwara, O. & Khang, D.B. (1990). A Two-Phase Decomposition Method for Optimal Design of Looped Water Distribution Networks. *Water Resources Research*, Vol.26, No.4, pp. 539-549

Geem, Z.W., Kim J.H. & Loganathan, G.V. (2003). Harmony search optimization: application to pipe network design. *International Journal of Modelling and Simulation*, Vol.22, No.2, pp. 125-133

González-Cebollada, C., Macarulla, B. & Sallán D. (2011). Recursive Design of Pressurized Branched Irrigation Networks. *Journal of Irrigation and Drainage Engineering*, Vol. 137, No. 6, June 1, pp. 375 – 382

Izquierdo, J., Montalvo, I., Peacuterez R. & Iglesias, P.L. (2008). A diversity-enriched variant of discrete PSO applied to the design of water distribution networks. *Engineering Optimization*, Vol.40, No.7, pp. 655-668

Kennedy, J., Eberhart, R. & Shi, Y. (2001). *Swarm Intelligence*. San Diego, CA: Academic Press

Kessler, A. & Shamir, U. (1989). Analysis of the Linear Programming Gradient Method for Optimal Design of Water Supply Networks. *Water Resources Research*, Vol.25, No.7, pp. 1469-1480

Labye, Y. (1966). Etude des procedés de calcul ayant pour but de rendre minimal le cout d'un reseau de distribution d'eau sous pression, La Houille Blanche 5, pp. 577–583

Lansey, K.E. (2000). Optimal Design of Water Distribution Systems, In "Water Distribution Systems Handbook", Mays, L.W (editor), McGraw-Hill, New York,.

Loganathan, G.V., Greene J.J. & Ahn, T.J. (1995). Design heuristic for globally minimum cost water-distribution systems. *Journal of Water Resources Planning and Management*, Vol.121, No.2, pp. 182–192

Luitel, B. & Venayagamoorthy, G. (2008). Differential evolution particle swarm optimization for digital filter design. *Proceedings of IEEE Congress on Evolutionary Computation*, Hong Kong, China, June 1-6, 3954–3961

Maier, H.R., Simpson, A.R., Foong, W.K., Phang, K.Y., Seah, H.Y., & Tan, C.L. (2001). Ant colony optimization for the design of water distribution systems. *Proceedings of the World Water and Environmental Resources Congress*, Orlando, Florida, May 20-24

Moore, P. & Venayagamoorthy, G. (2006). Evolving digital circuits using hybrid particle swarm optimization and differential evolution. *International Journal of Neural Systems*, Vol.16, No.3, pp. 163–177

Reca, J., Martínez, J., Gil, C., Baños, R. (2008). Application of several meta-heuristic techniquess to the optimization of real looped water distribution networks. *Water Resources Management,* Vol.22, No.10, pp. 1367–1379

Rossman, L. A (2000). *EPANET User's Manual*, U.S. Environmental Protection Agency

Savic, D.A. & Walters, G.A. (1997). Genetic algorithms for least-cost design of water distribution networks. *Journal of Water Resources Planning and Management*, ASCE, Vol. 123, No.2, pp. 67-77

Simpson, A.R., Dandy, G.C., Murphy, L.J. (1994). Genetic algorithms compared to other techniques for pipe optimization. *Journal of Water Resources Planning and Management*, ASCE, Vol.120, No.4, (July/August)

Storn, R. & Price, K. (1997). Differential evolution: A simple and efficient heuristic for global optimization over continuous spaces. *Journal of Global Optimization*, Vol.11, No.4, pp. 341-359,.

Theocharis, M.E., Tzimopoulos, C.D., Sakellariou-Makrantonaki, M.A., Yannopoulos, S.I., Meletiou, I.K. (2005). Comparative calculation of irrigation networks using Labye's method, the linear programming method and a simplified nonlinear method, *Mathematical and Computer Modelling*, Vol.51, No.3-4, pp. 286-299, ISSN 0895-7177

Xu, R., Venayagamoorthy, G. & Wunsch II, D. (2007). Modeling of gene regulatory networks with hybrid differential evolution and particle swarm optimization. *Neural Networks,* Vol. 20, No.8, pp. 917–927

Xu, R., Xu, J., Wunsch, D.C., (2010). Clustering with differential evolution particle swarm optimization. Evolutionary Computation (CEC), 2010 IEEE World Congress on Comutational Inteligence, Barcelona, Spain, July 18-23

Zdražil K.1986. Research of the computation and graphical methods of designing the irrigation pipe networks. VUZH Bratislava. In Czech.

Zecchin, A.C., Maier, H.R., Simpson, A.R., Leonard, M. & Nixon, J.B. (2007). Ant colony optimization applied to water distribution system design: comparative study of five algorithms. *Journal of Water Resources Planning and Management*, Vol. 133, No.1, pp. 87-92

Zhang W. & Xie, X. (2003). DEPSO: Hybrid particle swarm with differential evolution operator. *Proceedings of IEEE International Conference on Systems, Man, and Cybernetics*, Washington D C, USA, 2003, pp. 3816–3821

An Algebraic Approach for Controlling Cascade of Reaches in Irrigation Canals

Mouhamadou Samsidy Goudiaby[1], Abdou Sene[1] and Gunilla Kreiss[2]
[1]*LANI, UFR SAT, Université Gaston Berger, Saint-Louis*
[2]*Division of Scientific Computing, Department of Information Technology, Uppsala University, Uppsala*
[1]*Senegal*
[2]*Sweden*

1. Introduction

Due to the lack of water resources, the problem of water management and minimizing the losses becomes an attraction for many researchers. Although some problems have been already solved in the theoritical point of view, only few of the proposed solutions have been effectively tested in a real situation (Litrico et al., 2003). Limitations of water control technology have been discussed in (Gowing., 1999). However, there are problems that have not been solved yet, as reported in (Bastin et al., 2009). Those problems concern both technological applications and mathematical challenges. To solve water management problems, the so-called St. Venant equations (De Saint-Venant., 1871) are often used as a fondamental tool to describe the dynamics of canals and rivers. They are composed by a 2×2 system of hyperbolic partial differential equations.

For a long time, the matter of controlling water level and flow in open canals has been considered in the literature. Various methods have been used to design boundary controllers which satisfy farmers or navigability demands. Among those different methods, we have: LQ (Linear Quadratic) control that has been particularly developped and studied by (Balogun et al., 1988), and (Malaterre., 1998) (see also (Weyer., 2003) and (Chen et al., 2002)). (Weyer., 2003) has considered LQ control of an irrigation canal in which the water levels are controlled using overshot gates located along the canal. A LQ control problem for linear symmetric infinite-dimensional systems has been considered by (Chen et al., 2002). PI (proportional and integral) control method has been used by (Xu & Sallet., 1999) to propose an output feedback controller using a linear PDE model around a steady state. Such an approach has been considered by (Litrico et al., 2003), where the authors expose and validate a methodology to design efficient automatic controllers for irrigation canals. Riemann and Lyapunov approaches are also considered (Leugering & Schmidt., 2002), (De Halleux et al., 2003), and recently by (Cen & Xi., 2009) and (Bastin et al., 2009).

For networks of open canals, many results have been shown by researchers using some of the methods mentionned above. For example, (De Halleux et al., 2003) have used the Riemann approach to deduce a stabilization control, for a network made up by several interconnected reaches in cascade (also (Cen & Xi., 2009) and reference cited therein). (Bastin et al., 2009) have used the Lyapunov stability approach to study the exponential stability (in L2-norm) of the classical solutions of the linearised Saint-Venant equations for the same network with a sloping bottom. (Leugering & Schmidt., 2002) have studied stabilization and null controlability of pertubations around a steady state for a star configuration network. Star configuration network can also be found in (Li., 2005) and (Goudiaby et al., -). (Goudiaby et al., -), have used a new approach to design boundary feedback controllers which stabilize the water flow and level around a given steady state.

Concerning network made up by several interconnected reaches in cascade, we have noticed, in the theoritical point of view, two approaches that are the Riemann invariants (De Halleux et al., 2003) and Lyapunov Analysis approaches (Bastin et al., 2009), (Cen & Xi., 2009). The purpose of this paper is to apply the approach given in (Goudiaby et al., -) to that network. The approach is applied to a network of two reaches but it can be generalize. Choosing a different type of network requires different treatment of junction where canals met together. On the other hand, the Saint-Venant equations considered in the present paper are in the non-conservation form. We consider the velocity at the boundaries as the controllable quantities.

The approach consists in expressing the rate of change of energy of the linearized problem, as a second order polynomial in terms of the flow velocity at the boundaries. The polynomial is handled in such a way to construct boundary feedback controllers that result in the water flow and the height approaching a given steady state. The water levels at the boundaries and at the junction are used to build the controllers. After deriving the controllers, we numerically apply them to a real problem, which is nonlinear, in order to investigate the robustness and flexibility of the approach.

The paper is organized as follows. In section 2, we present the network and the equations. We discuss how to determine a steady state solution and derive the linearized system and corresponding characteristic variables, on which controllers are built. We also formulate the main result, stating controllers and corresponding energy decay rates. In section 3, we demonstrate the approach by proving a corresponding result for a single reach, while the case of the network is proven in section 4. Numerical results obtained by a high order finite volume method (Leveque., 2002; Toro., 1999) are presented in section 5.

2. Governing equations and main result

The network can be given by Figure 1 or by any type of network where several reaches are interconnected in cascade (see (Bastin et al., 2009; De Halleux et al., 2003)). In Figure 1, M is considered as the junction node. The network model is given by the 1D St. Venant equations in each reach ($i = 1, 2$) and a flow conservation condition at M. The following variables are used: h_i is the height of the fluid column (m), v_i is the flow velocity (ms^{-1}), L_i is the length of the reach (m). The one dimensional St. Venant equations considered in the present paper are the following:

$$\begin{cases} \dfrac{\partial h_i}{\partial t} + \dfrac{\partial (v_i h_i)}{\partial x} = 0, & \text{in} \quad [0, L_i] \\[2ex] \dfrac{\partial v_i}{\partial t} + \dfrac{1}{2}\dfrac{\partial v_i^2}{\partial x} + g\dfrac{\partial h_i}{\partial x} = 0, & \text{in} \quad [0, L_i] \end{cases} \tag{1}$$

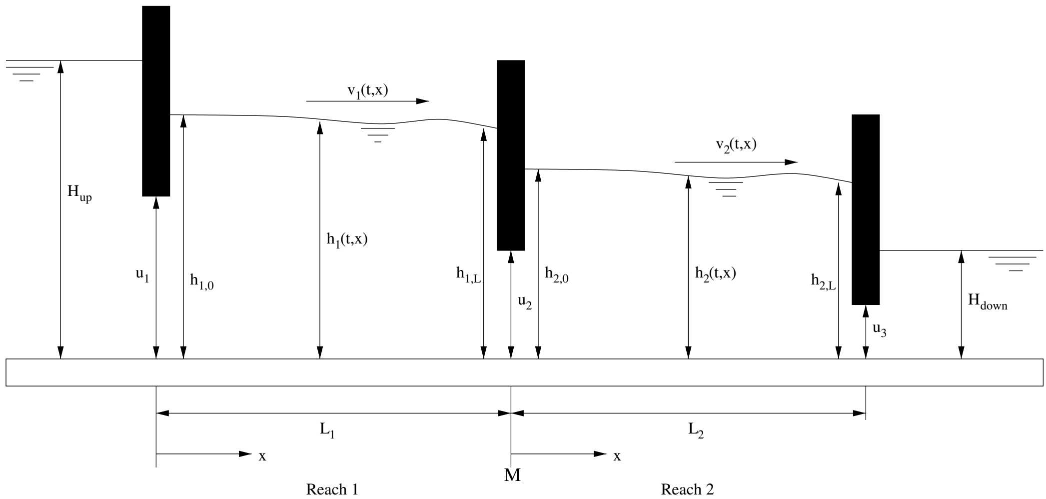


Fig. 1. The cascade network

together with a flow conservation condition at M,

$$h_1(t, L_1)v_1(t, L_1) = h_2(t, 0)v_2(t, 0), \tag{2}$$

initial conditions

$$h_i(0, x) = h_i^0(x), \quad v_i(0, x) = v_i^0(x), \tag{3}$$

and boundary conditions

$$v_1(t, 0) = v_{1,0}(t), \quad v_1(t, L_1) = v_{1,L_1}(t), \quad v_2(t, L_2) = v_{2,L_2}(t). \tag{4}$$

The results in the present paper concern a linearized system around a desired steady state. The controllers are built using that linear system and will be applied numerically to the above nonlinear model.

2.1 Steady state

The goal is to achieve a prescribed steady state $(\bar{h}_i, \bar{v}_i)$, with the help of the controllers, when time goes to infinity. From (1), the steady state solution $(\bar{h}_i, \bar{v}_i)$ satisfies:

$$\begin{cases} \dfrac{\partial \bar{v}_i}{\partial x} = 0, & \text{in} \quad [0, L_i], \\ \dfrac{\partial \bar{h}_i}{\partial x} = 0, & \text{in} \quad [0, L_i]. \\ \bar{h}_1(L_1)\bar{v}_1(L_1) = \bar{h}_2(0)\bar{v}_2(0) & \text{at} \quad M. \end{cases} \tag{5}$$

The steady state is such that

$$\bar{h}_2 < \bar{h}_1. \tag{6}$$

To determine the stady state (5), one gives $\bar{h}_1$, $\bar{v}_1$ and $\bar{h}_2$. On the other hand, using the flow direction (Figure 1) and the subcritical flow condition, one has

$$\bar{v}_i \geq 0 \quad \text{and} \quad \sqrt{g\bar{h}_i} > \bar{v}_i. \tag{7}$$

2.2 Linearized model

We introduce the residual state $(\check{h}_i, \check{v}_i)$ as the difference between the present state (h_i, v_i) and the steady state $(\bar{h}_i, \bar{v}_i)$: $\check{h}_i(t,x) = h_i(t,x) - \bar{h}_i(x)$, $\check{v}_i(t,x) = v_i(t,x) - \bar{v}_i(x)$. We use the assumptions $|\check{h}_i| \ll \bar{h}_i$ and $|\check{v}_i| \ll |\bar{v}_i|$ to linearize (1)-(4). Therefore, the solution $(\check{h}_i, \check{v}_i)$ satisfies

$$\begin{cases} (a)\ \dfrac{\partial \check{h}_i}{\partial t} + \bar{h}\dfrac{\partial \check{v}_i}{\partial x} + \bar{v}_i\dfrac{\partial \check{h}_i}{\partial x} = 0, \\ \\ (b)\ \dfrac{\partial \check{v}_i}{\partial t} + \bar{v}_i\dfrac{\partial \check{v}_i}{\partial x} + g\dfrac{\partial \check{h}_i}{\partial x} = 0, \\ \\ (c)\ \bar{v}_1\check{h}_1(t,L_1) + \bar{h}_1\check{v}_1(t,L_1) = \bar{v}_2\check{h}_2(t,0) + \bar{h}_2\check{v}_2(t,0) \quad \text{at} \quad M \end{cases} \tag{8}$$

together with the initial condition

$$\check{h}_i(0,x) = \check{h}_i^0(x), \quad \check{v}_i(0,x) = \check{v}_i^0(x), \tag{9}$$

and the boundary conditions as control laws

$$\check{v}_1(t,0) = \check{v}_{1,0}(t), \quad \check{v}_1(t,L_1) = \check{v}_{1,L_1}(t), \quad \check{v}_2(t,L_2) = \check{v}_{2,L_2}(t). \tag{10}$$

The functions $\check{v}_{1,0}(t)$, $\check{v}_{1,L_1}(t)$ and $\check{v}_{2,L_2}(t)$ are the feedback control laws to be prescribed in such a way to get an exponential convergence of $(\check{h}_i, \check{v}_i)$ to zero in time.

2.3 Eigenstructure and characteristic variables

The following characteristic variables are used to build the controllers:

$$\xi_{i1} = \check{v}_i - \check{h}_i\sqrt{\frac{g}{\bar{h}_i}} \qquad \text{and} \qquad \xi_{i2} = \check{v}_i + \check{h}_i\sqrt{\frac{g}{\bar{h}_i}}. \tag{11}$$

The characteristic velocities are

$$\lambda_{i1} = \bar{v}_i - \sqrt{g\bar{h}_i} \qquad \text{and} \qquad \lambda_{i2} = \bar{v}_i + \sqrt{g\bar{h}_i}.$$

The subcritical flow condition and the flow direction give

$$\lambda_{i1} < 0 < \lambda_{i2} \quad \text{and} \quad \lambda_{i1} + \lambda_{i2} \geq 0, \tag{12}$$

respectively. The characteristic variables satisfy

$$\frac{d\xi_{ij}}{dt} = \frac{\partial \xi_{ij}}{\partial t} + \lambda_{ij}\frac{\partial \xi_{ij}}{\partial x} = 0, \quad i,j = 1,2. \tag{13}$$

2.4 Main result

To build the feedback controllers, we express outgoing characteristic variables at the free endpoints and at the junction M in terms of initial data and the solution at the endpoints and at the junction M at earlier times. For reach 1, the outgoing characteristic variable at the endpoint $x = 0$ is ξ_{11}. For reach 2, the outgoing characteristic variable at the endpoint $x = L_2$ is ξ_{22}. Concerning the junction M, ξ_{12} and ξ_{21} are the outgoing characteristic variables. In section 4, we will see that

$$\begin{pmatrix} \xi_{11}(t,0) \\ \xi_{22}(t,L_2) \\ \xi_{12}(t,L_1) \\ \xi_{21}(t,0) \end{pmatrix} = \begin{pmatrix} b_1(t) \\ b_2(t) \\ b_3(t) \\ b_4(t) \end{pmatrix}, \tag{14}$$

where $b_i, i = 1,2,3,4$ depend only on the initial condition and the solution at the endpoints and at the junction M at earlier times $\tau = t - \delta t$ with $\delta t \geq \min\left(\frac{L_1}{\lambda_{12}}, \frac{L_2}{\lambda_{22}}\right)$.

Let us consider $\theta_1 : \mathbb{R}^+ \longrightarrow]0,1]$ satisfying:

$$\theta_1(t) \geq \frac{2\bar{v}_1}{\lambda_{12}}. \tag{15}$$

and $\theta_2,\ \theta_3 : \mathbb{R}^+ \longrightarrow]0,1]$ two arbitrary functions. We choose the feedback controllers as follows:

$$\begin{aligned}
\check{v}_{1,0}(t) &= -\frac{b_1(t)}{2}\left(\sqrt{1-\theta_1(t)} - 1\right), \\
\check{v}_{2,L_2}(t) &= -\frac{b_2(t)}{2}\left(\sqrt{1-\theta_2(t)} - 1\right), \\
\check{v}_{1,L_1}(t) &= \frac{\gamma(t)}{2\sigma}\left(\sqrt{1-\theta_3(t)} - 1\right),
\end{aligned} \tag{16}$$

where ,

$$\sigma = \bar{h}_1|\lambda_{11}|\left(1 + \frac{|\lambda_{11}|}{\lambda_{22}}\right), \qquad \gamma(t) = \bar{h}_1|\lambda_{11}|\left(1 - \frac{2\bar{v}_1}{\lambda_{22}}\right)b_3(t) + |\lambda_{11}|\sqrt{\bar{h}_1\bar{h}_2}\left(1 - \frac{2\bar{v}_2}{\lambda_{22}}\right)b_4(t),$$

and $b_i,\ i = 1,2,3,4$, are given by (14). Therefore, defining

$$T = \max\left(\frac{L_1}{|\lambda_{11}|}, \frac{L_2}{|\lambda_{21}|}\right), \tag{17}$$

and the energy of the network by

$$E = \sum_{i=1}^{2} E_i, \quad E_i = \int_0^{L_i}\left(g\check{h}_i^2(t) + \bar{h}_i\check{v}_i^2(t)\right)dx, \tag{18}$$

we get the main result of this paper:

Theorem 1. *Let $t_k = kT$, $k \in \mathbb{N}$, where T is given by (17). Assume that the flow in the network is subcritical, the initial condition $(\check{h}_i^0, \check{q}_i^0)$ is continuous in $]0, L_i[$, $\check{v}_{1,0}, \check{v}_{1,L_1}, \check{v}_{2,L_2}$ satisfy (16), θ_1 satisfies (15) and $\lambda_{i1} + \lambda_{i2} \geq 0$. Then (8)-(10) has a unique solution $(\check{h}_i, \check{q}_i)$ continuous in $[t_k, t_{k+1}] \times]0, L_i[$ satisfying the following energy estimate:*

$$E(t_{k+1}) \leq (1 - \Theta^k) E(t_k), \tag{19}$$

where E is given by (18) and

$$\Theta^k = \min\left(\Gamma_1^k, \Gamma_2^k\right) \in [0, 1[,$$

$$\Gamma_1^k = \min\left(\inf_{x \in]0, L_1[}\left(\theta_1(t_k + \frac{x}{|\lambda_{11}|}) - \frac{2\bar{v}_1}{\lambda_{12}}\right), 4\bar{v}_1 \frac{(\bar{v}_2 - \bar{v}_1)}{\lambda_{22}\lambda_{12}}\right),$$

$$\Gamma_2^k = \min\left(\inf_{x \in]0, L_2[}\left(\frac{|\lambda_{21}|}{\lambda_{22}}\theta_2(t_k + \frac{L_2 - x}{\lambda_{22}}) + \frac{2\bar{v}_2}{\lambda_{22}}\right), 2\frac{(\bar{v}_2 - \bar{v}_1)}{\lambda_{22}}\left(1 - \frac{2\bar{v}_2}{\lambda_{22}}\right)\right).$$

Remark 1.

1. *In addition to (19), within the interval $]t_k, t_{k+1}[$, the energy is non-increasing.*
2. *The controllers (16) tend to zero when time goes to infinity. This is due to (19) and the fact that they are built on the solution at earlier times.*
3. *Estimation (19) can be written as*

$$E(t_k) \leq E(0) \exp\left(-\mu^k \, t_k\right).$$

where $\mu^k = \frac{1}{k}\sum_{j=0}^{k-1} \nu^j$ and $\nu^j = -\ln\left((1 - \Theta^j)^{\frac{1}{t_1}}\right)$. Thus, the functions θ can be viewed as stabilization rate for the exponential decrease.

3. Building the controller for a single reach

We construct a stabilization process for a single canal, which should drive the perturbations $\check{h}$ and $\check{v}$ to zero exponentially in time. We consider the 1D Saint-Venant equations (1) without the index i standing for the reach number:

$$\begin{cases} \dfrac{\partial h}{\partial t} + \dfrac{\partial (vh)}{\partial x} = 0, \\[2ex] \dfrac{\partial v}{\partial t} + \dfrac{1}{2}\dfrac{\partial v^2}{\partial x} + g\dfrac{\partial h}{\partial x} = 0, \end{cases} \tag{20}$$

together with initial conditions

$$h(0, x) = h^0(x), \quad v(0, x) = v^0(x) \tag{21}$$

and boundary conditions

$$v(t, 0) = v_0(t), \quad v(t, L) = v_L(t). \tag{22}$$

The steady state solution $(\bar{h}, \bar{v})$ satisfies:

$$\frac{\partial \bar{v}}{\partial x} = 0, \quad \frac{\partial \bar{h}}{\partial x} = 0, \quad \text{in} \quad [0, L].$$

with

$$\bar{v} \geq 0 \quad \text{and} \quad \sqrt{g\bar{h}} > \bar{v}. \tag{23}$$

The linearized model is

$$\begin{cases} (a) \ \dfrac{\partial \check{h}}{\partial t} + \bar{h}\dfrac{\partial \check{v}}{\partial x} + \bar{v}\dfrac{\partial \check{h}}{\partial x} = 0, \\ (b) \ \dfrac{\partial \check{v}}{\partial t} + \bar{v}\dfrac{\partial \check{v}}{\partial x} + g\dfrac{\partial \check{h}}{\partial x} = 0, \end{cases} \tag{24}$$

together with initial conditions

$$\check{h}(0, x) = \check{h}^0(x), \quad \check{v}(0, x) = \check{v}^0(x), \tag{25}$$

and the boundary conditions

$$\check{v}(t, 0) = \check{v}_0(t), \quad \check{v}(t, L) = \check{v}_L(t). \tag{26}$$

The functions $\check{v}_L(t)$ and $\check{v}_0(t)$ are the feedback control laws to be prescribed in such a way to get an exponential convergence of $(\check{h}, \check{v})$ to zero in time.

The characteristic variables are:

$$\xi_1 = \check{v} - \check{h}\sqrt{\frac{g}{\bar{h}}} \qquad \text{and} \qquad \xi_2 = \check{v} + \check{h}\sqrt{\frac{g}{\bar{h}}}, \tag{27}$$

with the characteristic velocities

$$\lambda_1 = \bar{v} - \sqrt{g\bar{h}} \qquad \text{and} \qquad \lambda_2 = \bar{v} + \sqrt{g\bar{h}}.$$

The subcritical flow condition and the flow direction give

$$\lambda_1 < 0 < \lambda_2 \quad \text{and} \quad \lambda_1 + \lambda_2 \geq 0, \tag{28}$$

respectively. Considering the characteristic variables (27), system (24) is written as two independant equations:

$$\frac{d\xi_j}{dt} = \frac{\partial \xi_j}{\partial t} + \lambda_j \frac{\partial \xi_j}{\partial x} = 0, \quad j = 1, 2. \tag{29}$$

3.1 A priori energy estimation

Let E be the energy of (24) defined as

$$E(t) = \int_0^L \left(g\check{h}^2(t) + \bar{h}\check{v}^2(t) \right) dx. \tag{30}$$

We consider the following system as a weak formulation of (24)

$$\begin{cases} \forall(\psi,\phi) \in H^1(]0,L[), \\ \displaystyle\int_0^L g\psi \frac{\partial \check{h}}{\partial t}\,dx - g\bar{h}\int_0^L \check{v}\frac{\partial(\psi)}{\partial x}\,dx - g\bar{v}\int_0^L \check{h}\frac{\partial(\psi)}{\partial x}\,dx + \\ \qquad g\bar{h}\psi(L)\check{v}_L(t) - g\bar{h}\psi(0)\check{v}_0(t) + g\bar{v}\psi(L)\check{h}_L(t) - g\bar{v}\psi(0)\check{h}_0(t) = 0, \\ \displaystyle\int_0^L \bar{h}\phi\frac{\partial \check{v}}{\partial t}\,dx - \bar{h}\bar{v}\int_0^L \check{v}\frac{\partial(\phi)}{\partial x}\,dx - g\bar{h}\int_0^L \check{h}\frac{\partial(\phi)}{\partial x}\,dx \\ \qquad +\bar{h}\bar{v}\phi(L)\check{v}_L(t) - \bar{h}\bar{v}\phi(0)\check{v}_0(t) + g\bar{h}\phi(L)\check{h}_L(t) - g\bar{h}\phi(0)\check{h}_0(t) = 0, \end{cases} \tag{31}$$

together with boundary and initial conditions.

We estimate the variation of the energy E on the canal in order to define the controllers $\check{v}_L(t)$ on $\{x = L\}$ and $\check{v}_0(t)$ on $\{x = 0\}$. To this end, we let $(\psi,\phi) = (\check{h},\check{v})$ in (31) to get

$$\begin{aligned} \frac{1}{2}\frac{d}{dt}E(t) = &-\frac{\bar{h}\bar{v}}{2}\check{v}_L^2(t) - \frac{g\bar{v}}{2}\check{h}^2(t,L) - g\bar{h}\check{h}(t,L)\check{v}_L(t) \\ &+\frac{\bar{h}\bar{v}}{2}\check{v}_0^2(t) + \frac{g\bar{v}}{2}\check{h}^2(t,0) + g\bar{h}\check{h}(t,0)\check{v}_0(t). \end{aligned} \tag{32}$$

The difference among control methods depends on how the energy is defined and its variation handled to obtain a convergence of the perturbations $\check{h}$ and $\check{v}$ to zero in time (see (Bastin et al., 2009; De Halleux et al., 2003)).

3.2 Controllers and the stabilization process

The feedback control building relies on the fact that we can express the height at the boundaries in terms of the flow velocity and outgoing characteristic variables. Using (29)

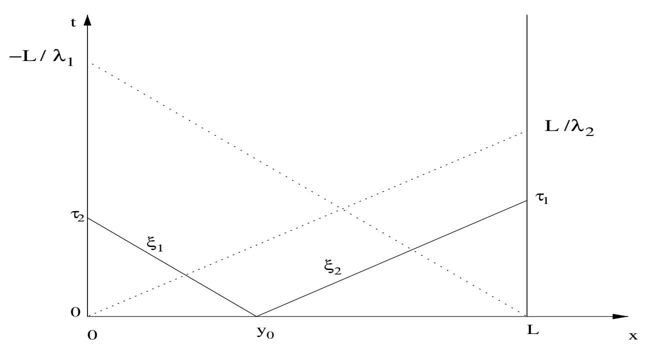


Fig. 2. Characteristic variables.

and refering on the characteristic variables indicated in figure 2, one has:

$$\begin{pmatrix} \xi_1(\tau_2,0) \\ \xi_2(\tau_1,L) \end{pmatrix} = \begin{pmatrix} b_1(\tau_2) \\ b_2(\tau_1) \end{pmatrix}, \tag{33}$$

where

$$b_1(\tau_2) = \begin{cases} \xi_1(0, |\lambda_1|\tau_2), & \tau_2 \leq \frac{L}{|\lambda_1|}, \\ \xi_1(\tau_2 - \frac{L}{|\lambda_1|}, L), & \tau_2 \geq \frac{L_1}{|\lambda_1|}, \end{cases} \qquad b_2(\tau_1) = \begin{cases} \xi_2(0, L - \lambda_2\tau_1), & \tau_1 \leq \frac{L}{\lambda_2}, \\ \xi_2(\tau_1 - \frac{L}{\lambda_2}, 0), & \tau_1 \geq \frac{L}{\lambda_2}. \end{cases} \tag{34}$$

From (27), one derives

$$\check{h}(\tau_1, L) = \Big(\xi_2(\tau_1, L) - v_L(\tau_1)\Big)\sqrt{\frac{\bar{h}}{g}}, \tag{35}$$

$$\check{h}(\tau_2, 0) = \Big(-\xi_1(\tau_2, 0) + v_0(\tau_2)\Big)\sqrt{\frac{\bar{h}}{g}}. \tag{36}$$

Considering the energy equation (32), one deduces from (34)-(36) that

$$\frac{1}{2}\frac{dE}{dt}(t) = a_1\check{v}_0^2(t) - a_1 b_1(t)\check{v}_0(t) + c_1(t) + a_2\check{v}_L^2(t) - a_2 b_2(t)\check{v}_L(t) + c_2(t) \tag{37}$$

where

$$a_1 = \bar{h}\lambda_2, \quad a_2 = \bar{h}|\lambda_1|, \quad c_1(t) = \frac{\bar{h}\bar{v}}{2}b_1^2(t), \quad c_2(t) = -\frac{\bar{h}\bar{v}}{2}b_2^2(t), \tag{38}$$

$b_1(t)$ and $b_2(t)$ are given by (34).

The RHS of (37) is treated in such a way to get an exponential decrease of the energy. For this propose, the following observation for second order polynomials is used.

Lemma 1. *Consider a second order polynomial $P(q) = av^2 + bv$, where $a > 0$. For any $\theta \in [0, 1]$*

$$P\left(\frac{b}{2a}(\sqrt{1-\theta} - 1)\right) = -\frac{b^2}{4a}\theta. \tag{39}$$

If the flow velocity at the boundary is prescribed as follows:

$$\check{v}_L(t) = -\frac{b_2(t)}{2}\left(\sqrt{1-\theta_2(t)} - 1\right) \quad \text{and} \quad \check{v}_0(t) = -\frac{b_1(t)}{2}\left(\sqrt{1-\theta_1(t)} - 1\right), \tag{40}$$

where $\theta_1, \theta_2 : \mathbb{R}^+ \longrightarrow [0, 1]$, then by Lemma 1, (37) becomes

$$\begin{aligned} \frac{1}{2}\frac{dE}{dt}(t) &= -\frac{b_1^2(t)}{4a_1}\theta_1(t) + c_1 - \frac{b_2^2}{4a_2}\theta_2(t) + c_2, \\ &= -\frac{\bar{h}}{4}\big(\lambda_2\theta_1(t) - 2\bar{v}\big)b_1^2(t) - \frac{\bar{h}}{4}\big(|\lambda_1|\theta_2(t) + 2\bar{v}\big)b_2^2(t). \end{aligned} \tag{41}$$

In order to get an energy decrease, we chosse θ_1 such that the RHS of (41) is non-positive. In fact we choose θ_1 as follows:

$$\theta_1(t) \geq \frac{2\bar{v}}{\lambda_2}. \tag{42}$$

Note that this choice of θ_1 is always possible since $\frac{2\bar{v}}{\lambda_2} < 1$. Indeed $\frac{2\bar{v}}{\lambda_2} < 1$, because the subcritical flow condition (23) gives $\lambda_2 = \sqrt{g\bar{h}} + \bar{v} > 2\bar{v}$. Thus, we get the following result

Theorem 2. *Let $t_k = kL/|\lambda_1|$, $k \in \mathbb{N}$. Assume that (28) holds, the initial condition $(\check{h}^0, \check{v}^0)$ is continuous in $]0, L[$, $(\check{v}_0, \check{v}_L)$ satisfies (40) and θ_1 satisfies (42). Then (24)-(26) has a unique solution $(\check{h}, \check{v})$ continuous in $[t_k, t_{k+1}]\times]0, L[$ satisfying the following energy estimate:*

$$E(t_{k+1}) \leq (1 - \Theta^k)E(t_k), \tag{43}$$

where E is given by (30) and

$$\Theta^k = \min\left(\inf_{x\in]0,L[}\left(\frac{|\lambda_1|}{\lambda_2}\theta_2(t_k + \frac{L-x}{\lambda_2}) + \frac{2\bar{v}}{\lambda_2}\right), \inf_{x\in]0,L[}\left(\theta_1\big(t_k + \frac{x}{|\lambda_1|}\big) - \frac{2\bar{v}}{\lambda_2}\right)\right) \in [0, 1[.$$

Proof: The existence and uniqueness of the solution follow by (27) and construction (33).

Integrating (41) from 0 to t_1, we have

$$\begin{aligned}
E(L/|\lambda_1|) &= E(0) - \frac{\bar{h}}{2}\int_0^{L/|\lambda_1|} \big(\lambda_2\theta_1(t) - 2\bar{v}\big)b_1^2(t)\,dt - \frac{\bar{h}}{2}\int_0^{L/|\lambda_1|} \big(|\lambda_1|\theta_2(t) + 2\bar{v}\big)b_2^2(t)\,dt,\\
&\leq E(0) - \frac{\bar{h}}{2}\int_0^{L/|\lambda_1|} \big(\lambda_2\theta_1(t) - 2\bar{v}\big)\xi_1^2(0, |\lambda_1|t)\,dt\\
&\qquad - \frac{\bar{h}}{2}\int_0^{L/\lambda_2} \big(|\lambda_1|\theta_2(t) + 2\bar{v}\big)\xi_2^2(0, L - \lambda_2 t)\,dt,\\
&\leq E(0) - \frac{\bar{h}}{2|\lambda_1|}\int_0^{L} \left(\lambda_2\theta_1(\frac{x}{|\lambda_1|}) - 2\bar{v}\right)\xi_1^2(0, x)\,dt\\
&\qquad - \frac{\bar{h}}{2\lambda_2}\int_0^{L} \left(|\lambda_1|\theta_2(\frac{L-x}{\lambda_2}) + 2\bar{v}\right)\xi_2^2(0, x)\,dt,\\
&\leq E(0) - \frac{\bar{h}}{2\lambda_2}\int_0^{L} \left(\lambda_2\theta_1(\frac{x}{|\lambda_1|}) - 2\bar{v}\right)\xi_1^2(0, x)\,dt\\
&\qquad - \frac{\bar{h}}{2\lambda_2}\int_0^{L} \left(|\lambda_1|\theta_2(\frac{L-x}{\lambda_2}) + 2\bar{v}\right)\xi_2^2(0, x)\,dt,\\
&\leq E(0) - \frac{\bar{h}}{2}\int_0^{L} \left(\theta_1(\frac{x}{|\lambda_1|}) - \frac{2\bar{v}}{\lambda_2}\right)\xi_1^2(0, x)\,dt\\
&\qquad - \frac{\bar{h}}{2}\int_0^{L} \left(\frac{|\lambda_1|}{\lambda_2}\theta_2(\frac{L-x}{\lambda_2}) + \frac{2\bar{v}}{\lambda_2}\right)\xi_2^2(0, x)\,dt,\\
&\leq E(0) - \frac{\bar{h}}{2}\int_0^{L} \left[\xi_2^2(0, x) + \xi_1^2(0, x)\right]\Theta^0 dx,
\end{aligned} \tag{44}$$

where

$$\Theta^0 = \min\left(\inf_{x\in]0,L[}\left(\frac{|\lambda_1|}{\lambda_2}\theta_2(\frac{L-x}{\lambda_2}) + \frac{2\bar{v}}{\lambda_2}\right), \inf_{x\in]0,L[}\left(\theta_1(\frac{x}{|\lambda_1|}) - \frac{2\bar{v}}{\lambda_2}\right)\right).$$

We have $\Theta^0 \in [0, 1[$, since we get $0 < \theta_1(\frac{x}{|\lambda_1|}) - \frac{2\bar{v}}{\lambda_2} < 1$ from (42) and the fact that $\frac{2\bar{v}}{\lambda_2} < 1$.

On the other hand, one has the following estimation

$$\xi_1^2(0,x) + \xi_2^2(0,x) = \left(\check{v}^0(x) - \check{h}^0(x)\sqrt{\frac{g}{\bar{h}}}\right)^2 + \left(\check{v}^0(x) + \check{h}^0(x)\sqrt{\frac{g}{\bar{h}}}\right)^2,$$

$$= 2(\check{v}^0(x))^2 + \frac{2g}{\bar{h}}(\check{h}^0(x))^2, = \frac{2}{\bar{h}}\left(\bar{h}(\check{v}^0(x))^2 + g(\check{h}^0(x))^2\right). \quad (45)$$

Therefore we deduce from (44)-(45) that

$$E(L/|\lambda_1|) \leq E(0) - \Theta^0 \int_0^L \left(\bar{h}(\check{v}^0(x))^2 + g(\check{h}^0(x))^2\right) dx \leq (1-\Theta^0)E(0). \quad (46)$$

In order to generalize (46) with respect to time, we consider the time $t_k = kL/|\lambda_1|$ as initial condition. Then, we let

$$b_1(t) = \xi_1(t_k, |\lambda_1|(t-t_k)), \quad if \quad t \in]t_k, t_k + L/|\lambda_1|[,$$

$$b_2(t) = \xi_2(t_k, L - \lambda_2(t-t_k)), \quad if \quad t \in]t_k, t_k + L/\lambda_2[,$$

and

$$\Theta^k = \min\left(\inf_{x\in]0,L[}\left(\frac{|\lambda_1|}{\lambda_2}\theta_2(t_k + \frac{L-x}{\lambda_2}) + \frac{2\bar{v}}{\lambda_2}\right), \inf_{x\in]0,L[}\left(\theta_1(t_k + \frac{x}{|\lambda_1|}) - \frac{2\bar{v}}{\lambda_2}\right)\right) \in [0,1[.$$

And, by integrating from t_k to t_{k+1} and using the same arguments as for the interval $[0,t_1]$, the proof of Theorem 2 is finished. □

Remark 2.

1. *Using the weak formulation (31) and the fact that $C^0(]0,L[)$ is dense in $L^2(]0,L[)$, it is possible (using the arguments of (Goudiaby et al., -)) to prove that for initial data $(\check{h}^0, \check{v}^0)$ in $(L^2(]0,L[))^2$, the solution $(\check{h}, \check{v})$ of (24)-(26) satisfies (43) and the following regularity*

$$\begin{pmatrix} \check{h} \\ \bar{h}\check{v} + \bar{v}\check{h} \end{pmatrix}, \quad \begin{pmatrix} \check{v} \\ \bar{v}\check{v} + g\check{h} \end{pmatrix} \in H(div, Q), \quad (47)$$

where $Q =]t_k, t_{k+1}[\times]0,L[$,

$$div \equiv \left(\frac{\partial}{\partial t}, \frac{\partial}{\partial x}\right) \quad and \quad H(div, Q) = \left\{\mathcal{V} \in L^2(Q)^2 ; div\,\mathcal{V} \in L^2(Q)\right\}.$$

2. *It is also possible to stabilize the reach by acting only on one free endpoint as in (Goudiaby et al., -).*
3. *Only the initial condition and the on-line measurements of the water levels at the endpoints are required to implement the feedback control law (40).*
4. *For an application need, in order to implement the controllers (40), one can use two underflow gates located at the left end $(x = 0)$ and the right end $(x = L)$ of the canal (see Fig 3). Denote by I_0 and I_L the gates opening. A relation between under flow gates opening and discharge is given as follows (see (De Halleux et al., 2003; Ndiaye & Bastin., 2004)).*

$$lh(t,0)v(t,0) = I_0(t)k_1\sqrt{2g(H_{up} - h(t,0))}, \quad (48)$$

$$lh(t,L)v(t,L) = I_L(t)k_2\sqrt{2g(h(t,L) - H_{down})}, \quad (49)$$

where, l is the width of the reach (m), k_1, k_2 are gate coefficients, $v(t,x) = \bar{v}(x) + \check{v}(t,x)$, $h(t,x) = \bar{h}(x) + \check{h}(t,x)$, H_{up} and H_{down} are the left and right water levels outside the canal, respectively. H_{up} and H_{down} are supposed to be constant and satisfy $H_{up} > h(t,0)$ and $h(t,L) > H_{down}$.

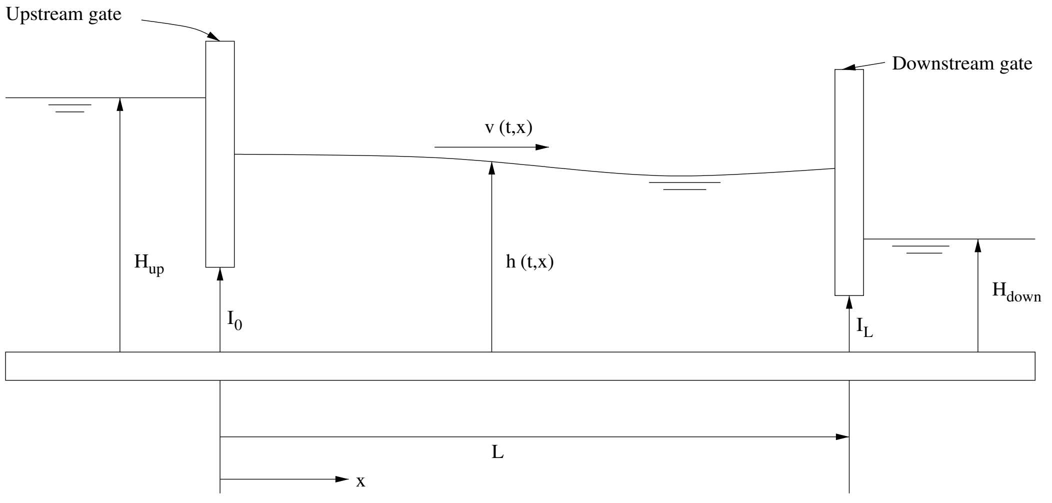


Fig. 3. A canal delimited by underflow gates

4. Building the controller for the cascade network

In this section, we use the idea of section 3.2, to build feedback control laws for the network.

4.1 Energy estimation and controllers building

Consider the energy of the network given by

$$E = \sum_{i=1}^{2} E_i, \quad E_i = \int_0^{L_i} \left(g\check{h}_i^2(t) + \bar{h}_i \check{v}_i^2(t) \right) dx. \tag{50}$$

Arguing as in section 3.1, from the weak formulation of (8), we deduce

$$\begin{aligned} \frac{1}{2}\frac{d}{dt}E(t) = & -\frac{\bar{h}_1\bar{v}_1}{2}\check{v}_{1,L_1}^2(t) - \frac{g\bar{v}_1}{2}\check{h}_1^2(t,L_1) - g\bar{h}_1\check{h}_1(t,L_1)\check{v}_{1,L_1}(t) \\ & + \frac{\bar{h}_1\bar{v}_1}{2}\check{v}_{1,0}^2(t) + \frac{g\bar{v}_1}{2}\check{h}_1^2(t,0) + g\bar{h}_1\check{h}_1(t,0)\check{v}_{1,0}(t) \\ & -\frac{\bar{h}_2\bar{v}_2}{2}\check{v}_{2,L_2}^2(t) - \frac{g\bar{v}_2}{2}\check{h}_2^2(t,L_2) - g\bar{h}_2\check{h}_2(t,L_2)\check{v}_{2,L_2}(t) \\ & + \frac{\bar{h}_2\bar{v}_2}{2}\check{v}_{2,0}^2(t) + \frac{g\bar{v}_2}{2}\check{h}_2^2(t,0) + g\bar{h}_2\check{h}_2(t,0)\check{v}_{2,0}(t). \end{aligned} \tag{51}$$

Using (13) and refering to figure 4, we express outgoing characteristic variables in terms of initial data and the solution at the endpoints and at the junction M at earlier times, i.e (14) is

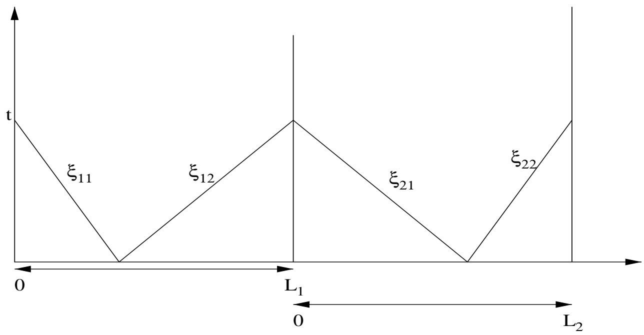


Fig. 4. Characteristic variables for the cascade network

satisfies with,

$$b_1(t) = \begin{cases} \xi_{11}(0, |\lambda_{11}|t), & t \leq \frac{L_1}{|\lambda_{11}|}, \\ \xi_{11}(t - \frac{L_1}{|\lambda_{11}|}, L_1), & t \geq \frac{L_1}{|\lambda_{11}|}. \end{cases} \quad b_2(t) = \begin{cases} \xi_{22}(0, L_2 - \lambda_{22}t), & t \leq \frac{L_2}{\lambda_{22}}, \\ \xi_{22}(t - \frac{L_2}{\lambda_{22}}, 0), & t \geq \frac{L_2}{\lambda_{12}}. \end{cases}$$

$$b_3(t) = \begin{cases} \xi_{12}(0, L_1 - \lambda_{12}t), & t \leq \frac{L_1}{\lambda_{12}}, \\ \xi_{12}(t - \frac{L_1}{\lambda_{12}}, 0), & t \geq \frac{L_1}{\lambda_{12}}. \end{cases} \quad b_4(t) = \begin{cases} \xi_{21}(0, |\lambda_{21}|t), & t \leq \frac{L_2}{|\lambda_{21}|}, \\ \xi_{21}(t - \frac{L_2}{|\lambda_{21}|}, L_2), & t \geq \frac{L_2}{|\lambda_{21}|}. \end{cases} \tag{52}$$

On the other hand, using (11) we also express the height at the boundaries and at the junction in terms of the flow velocity and outgoing characteristic variables:

$$\begin{aligned} \check{h}_i(t, L_i) &= \Big(\xi_{i2}(t, L_i) - v_{i,L_i}(t)\Big)\sqrt{\tfrac{\bar{h}_i}{g}}, \\ \check{h}_i(t, 0) &= \Big(-\xi_{i1}(t, 0) + v_{i,0}(t)\Big)\sqrt{\tfrac{\bar{h}_i}{g}}. \end{aligned} \tag{53}$$

Plugging (53) into (51), one gets

$$\begin{aligned} \frac{1}{2}\frac{dE}{dt}(t) = {} & a_1\check{v}_{1,0}^2(t) - a_1 b_1(t)\check{v}_{1,0}(t) + c_1(t) + a_2\check{v}_{2,L_2}^2(t) - a_2 b_2(t)\check{v}_{2,L_2}(t) + c_2(t) \\ & + a_3\check{v}_{1,L_1}^2(t) - a_3 b_3(t)\check{v}_{1,L_1}(t) + c_3(t) + a_4\check{v}_{2,0}^2(t) - a_4 b_4(t)\check{v}_{2,0}(t) + c_4(t) \end{aligned} \tag{54}$$

where

$$\begin{aligned} & a_1 = \bar{h}_1\lambda_{12}, \qquad a_2 = \bar{h}_2|\lambda_{21}|, \qquad a_3 = \bar{h}_1|\lambda_{11}|, \qquad a_4 = \bar{h}_2\lambda_{22}, \\ & c_1(t) = \frac{\bar{h}_1\bar{v}_1}{2}b_1^2(t),\ c_2(t) = -\frac{\bar{h}_2\bar{v}_2}{2}b_2^2(t),\ c_3(t) = -\frac{\bar{h}_1\bar{v}_1}{2}b_3^2(t),\ c_4(t) = \frac{\bar{h}_2\bar{v}_2}{2}b_4^2(t), \end{aligned} \tag{55}$$

$b_i, i = 1, 2, 3, 4$ are given by (52).

The flow conservation condition (8.c) is used to express $\check{v}_{2,0}$ in terms of $\check{v}_{1,L_1}$ and outgoing characteristic variables. From (8.c) and (53), one has

$$\check{v}_{2,0}(t) = \alpha\check{v}_{1,L_1}(t) + \beta b_3(t) + \delta b_4(t). \tag{56}$$

where

$$\alpha = \frac{|\lambda_{11}|}{\lambda_{22}}\sqrt{\frac{\bar{h}_1}{\bar{h}_2}}, \qquad \beta = \frac{\bar{v}_1}{\lambda_{22}}\sqrt{\frac{\bar{h}_1}{\bar{h}_2}}, \qquad \delta = \frac{\bar{v}_2}{\lambda_{22}}. \tag{57}$$

Thus, the last six terms of (54) can be expressed as follows:

$$\begin{aligned} a_3\check{v}^2_{1,L_1}(t) - a_3 b_3(t)\check{v}_{1,L_1}(t) + c_3(t) + a_4\check{v}^2_{2,0}(t) - a_4 b_4(t)\check{v}_{2,0}(t) + c_4(t) \\ = \sigma\check{v}^2_{1,L_1}(t) + \gamma(t)\check{v}_{1,L_1}(t) + \rho(t), \end{aligned} \tag{58}$$

where

$$\sigma = (a_3 + \alpha^2 a_4) = \bar{h}_1|\lambda_{11}|\left(1 + \frac{|\lambda_{11}|}{\lambda_{22}}\right) \tag{59}$$

$$\begin{aligned} \gamma(t) &= (2a_4\alpha\beta - \bar{h}_1|\lambda_{11}|)b_3(t) + \alpha(2a_4\delta - \bar{h}_2\lambda_{22})b_4(t) \\ &= \bar{h}_1|\lambda_{11}|\left(\frac{2\bar{v}_1}{\lambda_{22}} - 1\right)b_3(t) + |\lambda_{11}|\sqrt{\bar{h}_1\bar{h}_2}\left(\frac{2\bar{v}_2}{\lambda_{22}} - 1\right)b_4(t) \end{aligned} \tag{60}$$

$$\begin{aligned} \rho(t) &= \left(a_4\delta^2 - \bar{h}_2\lambda_{22}\delta + \frac{\bar{h}_2\bar{v}_2}{2}\right)b_4^2(t) + \left(a_4\beta^2 - \frac{\bar{h}_1\bar{v}_1}{2}\right)b_3^2(t) \\ &\quad + \beta(2a_4 - \bar{h}_2\lambda_{22})b_3(t)b_4(t) \\ &= \frac{\bar{h}_2\bar{v}_2}{2}\left(\frac{2\bar{v}_2}{\lambda_{22}} - 1\right)b_4^2(t) + \frac{\bar{h}_1\bar{v}_1}{2}\left(\frac{2\bar{v}_1}{\lambda_{22}} - 1\right)b_3^2(t) \\ &\quad + \bar{v}_1\sqrt{\bar{h}_1\bar{h}_2}\left(\frac{2\bar{v}_1}{\lambda_{22}} - 1\right)b_3(t)b_4(t). \end{aligned} \tag{61}$$

Taking into account (58), the energy law (54) becomes

$$\begin{aligned} \frac{1}{2}\frac{dE}{dt}(t) = a_1\check{v}^2_{1,0}(t) - a_1 b_1(t)\check{v}_{1,0}(t) + c_1(t) + a_2\check{v}^2_{2,L_2}(t) - a_2 b_2(t)\check{v}_{2,L_2}(t) + c_2(t) \\ + \sigma\check{v}^2_{1,L_1}(t) + \gamma(t)\check{v}_{1,L_1}(t) + \rho(t). \end{aligned} \tag{62}$$

If we prescribe the velocity at the boundaries as follows,

$$\begin{aligned} \check{v}_{1,0}(t) &= -\frac{b_1(t)}{2}\left(\sqrt{1 - \theta_1(t)} - 1\right), \\ \check{v}_{2,L_2}(t) &= -\frac{b_2(t)}{2}\left(\sqrt{1 - \theta_2(t)} - 1\right), \\ \check{v}_{1,L_1}(t) &= \frac{\gamma(t)}{2\sigma}\left(\sqrt{1 - \theta_3(t)} - 1\right), \end{aligned} \tag{63}$$

where $\theta_1,\ \theta_2,\ \theta_3:\ \mathbb{R}^+ \longrightarrow [0,1]$, it follows from Lemma 1 that

$$\frac{1}{2}\frac{dE}{dt}(t) = -\frac{b_1^2(t)}{4a_1}\theta_1(t) + c_1(t) - \frac{b_2^2(t)}{4a_2}\theta_2(t) + c_2(t) - \frac{\gamma^2(t)}{4\sigma}\theta_3(t) + \rho(t). \tag{64}$$

Let us calculate explicitely the RHS of (64). On the one hand, using (a_1, c_1) and (a_2, c_2) given in (55), we have

$$-\frac{b_1^2}{4a_1}\theta_1 + c_1 = -\frac{\bar{h}_1}{4}\left(\lambda_{12}\theta_1 - 2\bar{v}_1\right)b_1^2(t), \tag{65}$$

and

$$-\frac{b_2^2}{4a_2}\theta_2 + c_2 = -\frac{\bar{h}_2}{4}\left(|\lambda_{21}|\theta_2 + 2\bar{v}_2\right)b_2^2(t). \tag{66}$$

On the other hand, from (59)-(61) and using the fact that $\theta_3 \in]0,1]$ we have

$$\begin{aligned}-\frac{\gamma^2}{4\sigma}\theta_3 + \rho \le \rho = \frac{\bar{h}_2\bar{v}_2}{2}\left(\frac{2\bar{v}_2}{\lambda_{22}} - 1\right)b_4^2(t) + \frac{\bar{h}_1\bar{v}_1}{2}\left(\frac{2\bar{v}_1}{\lambda_{22}} - 1\right)b_3^2(t)\\ +\bar{v}_1\sqrt{\bar{h}_1\bar{h}_2}\left(\frac{2\bar{v}_1}{\lambda_{22}} - 1\right)b_3(t)b_4(t).\end{aligned} \tag{67}$$

Since $\frac{2\bar{v}_2}{\lambda_{22}} < 1$, we get

$$\bar{v}_1\sqrt{\bar{h}_1\bar{h}_2}\left(\frac{2\bar{v}_2}{\lambda_{22}} - 1\right)b_3(t)b_4(t) \le \frac{\bar{h}_1\bar{v}_1}{2}\left(1 - \frac{2\bar{v}_2}{\lambda_{22}}\right)b_3^2(t) + \frac{\bar{h}_2\bar{v}_1}{2}\left(1 - \frac{2\bar{v}_2}{\lambda_{22}}\right)b_4^2(t). \tag{68}$$

Combining (68) and (67), one has

$$-\frac{\gamma^2}{4\sigma}\theta_3 + \rho \le \bar{h}_1\bar{v}_1\frac{(\bar{v}_1 - \bar{v}_2)}{\lambda_{22}}b_3^2(t) + \frac{\bar{h}_2}{2}\left(\frac{2\bar{v}_2}{\lambda_{22}}(\bar{v}_2 - \bar{v}_1) - (\bar{v}_2 - \bar{v}_1)\right)b_4^2(t). \tag{69}$$

Using (65), (66) and (69), the energy law (64) becomes

$$\begin{aligned}\frac{1}{2}\frac{dE}{dt}(t) \le -\frac{\bar{h}_1}{4}\left(\left(\lambda_{12}\theta_1 - 2\bar{v}_1\right)b_1^2(t) + 4\bar{v}_1\frac{(\bar{v}_2 - \bar{v}_1)}{\lambda_{22}}b_3^2(t)\right)\\ -\frac{\bar{h}_2}{4}\left(2(\bar{v}_2 - \bar{v}_1)\left(1 - \frac{2\bar{v}_2}{\lambda_{22}}\right)b_4^2(t) + \left(|\lambda_{21}|\theta_2 + 2\bar{v}_2\right)b_2^2(t)\right).\end{aligned} \tag{70}$$

The way the steady state $(\bar{h}_1, \bar{v}_1, \bar{h}_2, \bar{v}_2)$ is chosen (see (6)), yields that

$$\bar{v}_2 \ge \bar{v}_1. \tag{71}$$

The function θ_1 satisfies a condition similar to (42), i.e

$$\theta_1(t) \ge \frac{2\bar{v}_1}{\lambda_{12}}. \tag{72}$$

Using the fact that $\frac{2\bar{v}_2}{\lambda_{22}} < 1$, (71) and (72), the RHS of (70) is non-positive. Thus we give the proof of Theorem 1.

4.2 Proof of theoreme 1

The existence and uniqueness of the solution follow by (11) and constructions (14).

Integrating (70) from 0 to t_1, one has

$$
\begin{aligned}
E(t_1) \;\leq\; & E(0) - \frac{\bar{h}_1}{2}\int_0^{t_1}\left(\lambda_{12}\theta_1(t) - 2\bar{v}_1\right)b_1^2(t)dt - \frac{\bar{h}_1}{2}\int_0^{t_1} 4\bar{v}_1\frac{(\bar{v}_2-\bar{v}_1)}{\lambda_{22}}b_3^2(t)dt \\
& -\frac{\bar{h}_2}{2}\int_0^{t_1} 2(\bar{v}_2-\bar{v}_1)\left(1-\frac{2\bar{v}_2}{\lambda_{22}}\right)b_4^2(t)dt - \frac{\bar{h}_2}{2}\int_0^{t_1}\left(|\lambda_{21}|\theta_2 + 2\bar{v}_2\right)b_2^2(t)dt. \\
\overset{(52)}{\leq}\; & E(0) - \frac{\bar{h}_1}{2}\int_0^{\frac{L_1}{|\lambda_{11}|}}\left(\lambda_{12}\theta_1(t) - 2\bar{v}_1\right)\xi_{11}^2(0,|\lambda_{11}|t)dt \\
& -\frac{\bar{h}_1}{2}\int_0^{\frac{L_1}{\lambda_{12}}} 4\bar{v}_1\frac{(\bar{v}_2-\bar{v}_1)}{\lambda_{22}}\xi_{12}^2(t, L_1-\lambda_{12}t)dt \\
& -\frac{\bar{h}_2}{2}\int_0^{\frac{L_1}{|\lambda_{21}|}} 2(\bar{v}_2-\bar{v}_1)\left(1-\frac{2\bar{v}_2}{\lambda_{22}}\right)\xi_{21}^2(t,|\lambda_{21}|t)dt \\
& -\frac{\bar{h}_2}{2}\int_0^{\frac{L_2}{\lambda_{22}}}\left(|\lambda_{21}|\theta_2(t) + 2\bar{v}_2\right)\xi_{22}^2(0, L_2-\lambda_{22}t)dt, \\
\leq\; & E(0) - \frac{\bar{h}_1}{2}\int_0^{L_1}\left(\theta_1\left(\frac{x}{|\lambda_{11}|}\right) - \frac{2\bar{v}_1}{\lambda_{12}}\right)\xi_{11}^2(0,x)dx \\
& -\frac{\bar{h}_1}{2}\int_0^{L_1} 4\bar{v}_1\frac{(\bar{v}_2-\bar{v}_1)}{\lambda_{22}\lambda_{12}}\xi_{12}^2(0,x)dx \\
& -\frac{\bar{h}_2}{2}\int_0^{L_2}\left(\frac{|\lambda_{21}|}{\lambda_{22}}\theta_2\left(\frac{L_2-x}{\lambda_{22}}\right) + \frac{2\bar{v}_2}{\lambda_{22}}\right)\xi_{22}^2(0,x)dx \\
& -\frac{\bar{h}_2}{2}\int_0^{L_2} 2\frac{(\bar{v}_2-\bar{v}_1)}{\lambda_{22}}\left(1-\frac{2\bar{v}_2}{\lambda_{22}}\right)\xi_{21}^2(0,x)dx. \\
\leq\; & E(0) - \frac{\bar{h}_1}{2}\int_0^{L_1}\left[\xi_{11}^2(0,x) + \xi_{12}^2(0,x)\right]\Gamma_1^0 dx \\
& -\frac{\bar{h}_2}{2}\int_0^{L_2}\left[\xi_{22}^2(0,x) + \xi_{21}^2(0,x)\right]\Gamma_2^0 dx, \qquad (73)
\end{aligned}
$$

where

$$
\Gamma_1^0 = \min\left(\inf_{x\in]0,L_1[}\left(\theta_1\left(\frac{x}{|\lambda_{11}|}\right) - \frac{2\bar{v}_1}{\lambda_{12}}\right), 4\bar{v}_1\frac{(\bar{v}_2-\bar{v}_1)}{\lambda_{22}\lambda_{12}}\right),
$$

$$
\Gamma_2^0 = \min\left(\inf_{x\in]0,L_2[}\left(\frac{|\lambda_{21}|}{\lambda_{22}}\theta_2\left(\frac{L_2-x}{\lambda_{22}}\right) + \frac{2\bar{v}_2}{\lambda_{22}}\right), 2\frac{(\bar{v}_2-\bar{v}_1)}{\lambda_{22}}\left(1-\frac{2\bar{v}_2}{\lambda_{22}}\right)\right).
$$

Arguing as for (45), we get

$$\xi_{i1}^2(0,x) + \xi_{i2}^2(0,x) = \frac{2}{\bar{h}_i}\left(\bar{h}_i(\check{v}_i^0(x))^2 + g(\check{h}_i^0(x))^2\right). \tag{74}$$

Therefore, using (74) in (73), one has

$$E(t_1) \leq (1 - \Theta^0)E(0) \tag{75}$$

where

$$\Theta^0 = \min\left(\Gamma_1^0, \Gamma_2^0\right) \in [0,1[, \quad \text{since} \quad 0 < \theta_1(\frac{x}{|\lambda_{11}|}) - \frac{2\bar{v}_1}{\lambda_{12}} < 1.$$

In order to generalize (75) with respect to time, we consider the time $t_k = kT$ as initial condition, with T given by (17). Then, we let

$$b_1(t) = \xi_{11}(t_k, |\lambda_{11}|(t - t_k)), \quad t \in]t_k, t_k + L_1/|\lambda_{11}|[,$$

$$b_2(t) = \xi_{22}(t_k, L_2 - \lambda_{22}(t - t_k)), \quad t \in]t_k, t_k + L_2/\lambda_{22}[,$$

$$b_3(t) = \xi_{12}(t_k, L_1 - \lambda_{12}(t - t_k)), \quad t \in]t_k, t_k + L_1/\lambda_{12}[,$$

$$b_3(t) = \xi_{21}(t_k, |\lambda_{21}|(t - t_k)), \quad t \in]t_k, t_k + L_2/|\lambda_{21}|[,$$

$$\Gamma_1^k = \min\left(\inf_{x\in]0,L_1[}\left(\theta_1(t_k + \frac{x}{|\lambda_{11}|}) - \frac{2\bar{v}_1}{\lambda_{12}}\right), 4\bar{v}_1\frac{(\bar{v}_2 - \bar{v}_1)}{\lambda_{22}\lambda_{12}}\right),$$

$$\Gamma_2^k(x) = \min\left(\inf_{x\in]0,L_2[}\left(\frac{|\lambda_{21}|}{\lambda_{22}}\theta_2(t_k + \frac{L_2 - x}{\lambda_{22}}) + \frac{2\bar{v}_2}{\lambda_{22}}\right), 2\frac{(\bar{v}_2 - \bar{v}_1)}{\lambda_{22}}\left(1 - \frac{2\bar{v}_2}{\lambda_{22}}\right)\right).$$

and

$$\Theta^k = \min\left(\Gamma_1^k, \Gamma_2^k\right) \in [0,1[.$$

Therefore, by integrating from t_k to t_{k+1} and using the same arguments as for the interval $[0, t_1]$, the proof of Theorem 1 is completed. □

5. Numerical results

Numerical results are obtained by using a high order finite volume method (see Leveque. (2002); Toro. (1999)).

5.1 A numerical example for a single reach

In this section, we illustrate the control design method on a canal with the following parameters. Lenght $L = 500m$, width $l = 1m$. The steady state is $\bar{q}(x) = 1m^3s^{-1}$ and $\bar{h}(x) = 1m$ and the initial condition is $h(0,x) = 2m$ and $q(0,x) = 3m^3s^{-1}$. The spatial step size is $\Delta x = 10m$ and the time step is $\Delta t = 1s$. We also set $H_{up} = 2.2m$ and $H_{down} = 0.5m$ and use relations (48)-(49) for gates opening.

We have tested a big perturbation in order to investigate the robusness and the flexibility of the control method. One sees that the bigger the θ's are, the faster the exponential deacrease is (Fig 5). Increasing θ's also produces some oscillations of the gates opening with heigh frequencies (Fig 6). We then notice that for the gates opening, choosing θ's between 0.5 and 0.7 gives a quite good behaviour of the gates opening (Fig 7-(b)). Generally, depending on the control action (gates, pumps etc) used, we can have a wide possibilities of choosing the θ's.

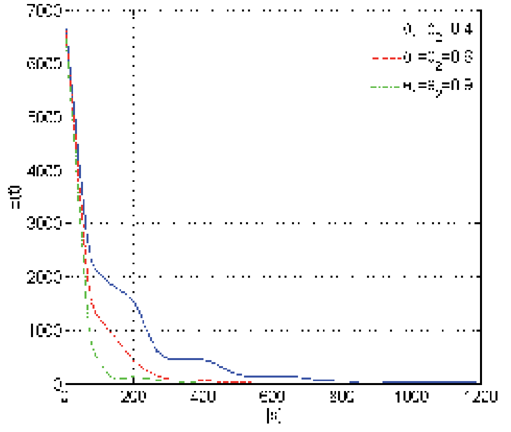
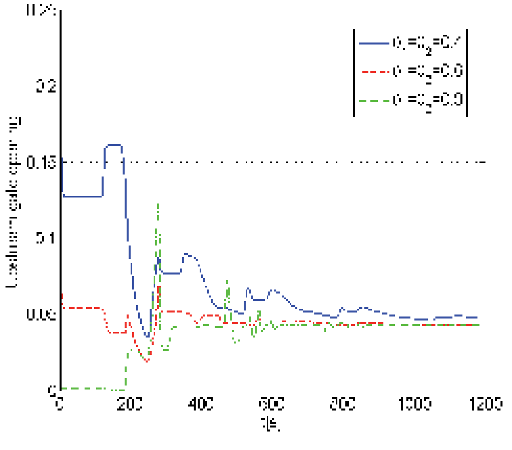
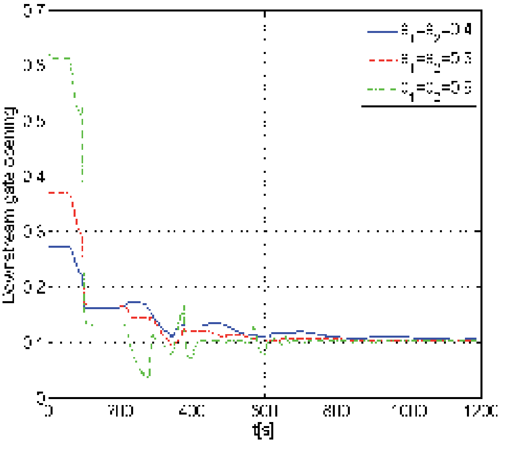


Fig. 5. Energy evolution for different values of θ_1 and θ_2.

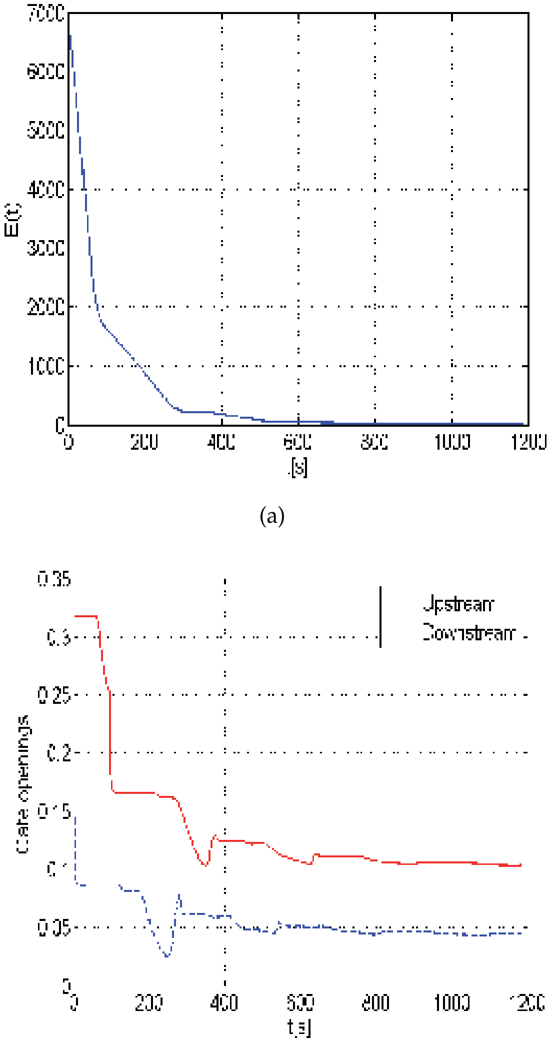


(a) Downstream gate opening



(b) Upstream gate opening

Fig. 6. Gate openings for different values of θ_1 and θ_2.



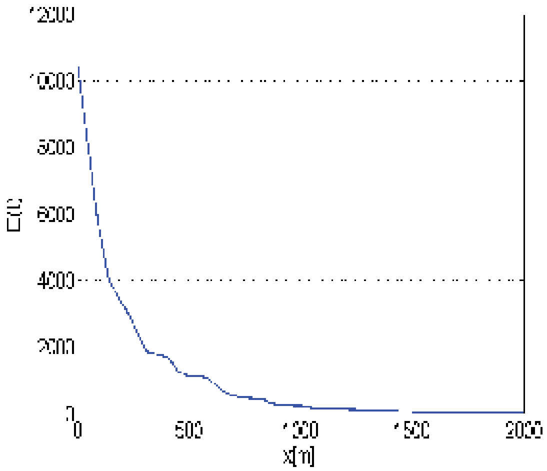
(a)

(b)

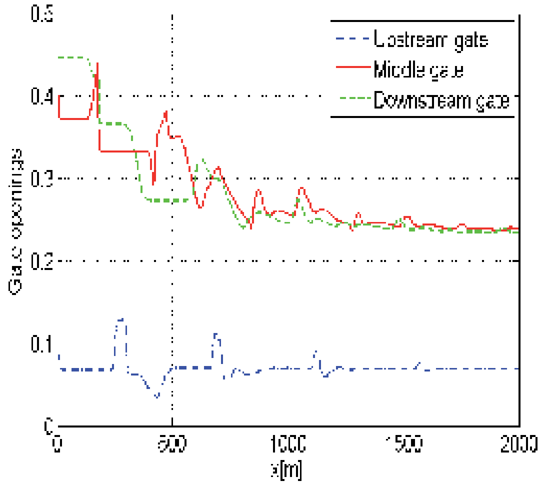
Fig. 7. Evolution of the energy (a) and gates opening (b) for $\theta_1 = \theta_2 = 0.5$.

5.2 A numerical example for the cascade network

We consider two reaches of Lenght $L_1 = L_2 = 1000m$, width $l = 1m$. The steady state is $\bar{q}_1(x) = 1.5m^3s^{-1}$, $\bar{h}_1(x) = 1.5m$ and $\bar{h}_2(x) = 1m$ and the initial condition is $h_1(0,x) = 2m$, $q_1(0,x) = 3m^3s^{-1}$, $h_2(0,x) = 1.5m$, $q_2(0,x) = 3m^3s^{-1}$. The spatial step size is $\Delta x = 10m$ and the time step is $\Delta t = 1s$. We also set $H_{up} = 3m$ and $H_{down} = 0.5m$. We have noticed as in the case of one single reach, that the bigger the θs are, the faster the exponential decrease is. In figure (8), we have plotted the energy decay and the gates opening for $\theta_1 = \theta_2 = \theta_3 = 0.7$. Although, the perturbations for reach 1 and 2 are different, the controllers act in such a way to drive the perturbations to zero simultaneously (Fig (9).



(a)



(b)

Fig. 8. Energy evolution (a) and gates opening (b) for $\theta_1 = \theta_2 = \theta_3 = 0.7$.

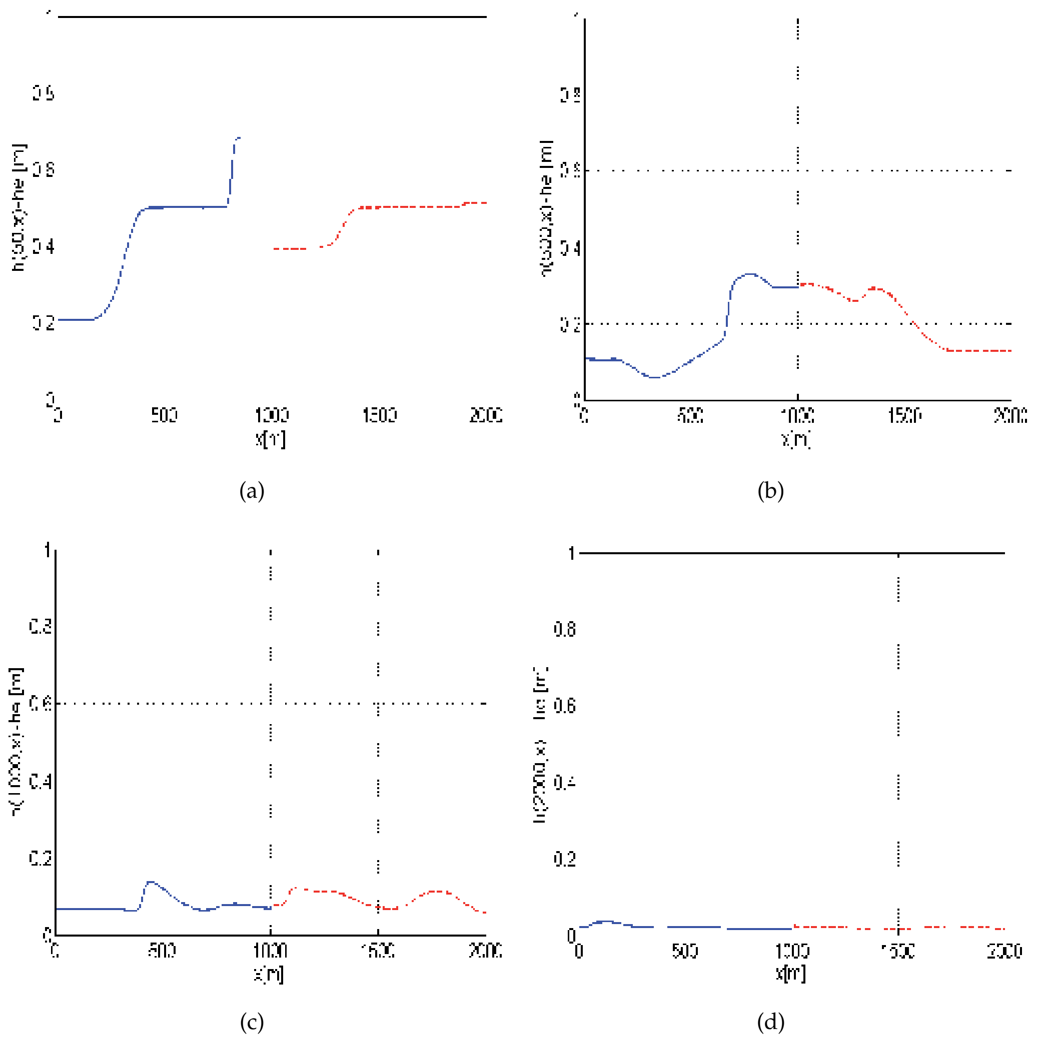


Fig. 9. Deviation of water height at instants $t = 50$ (a), $t = 500$ (b), $t = 1000$ (c) and $t = 2000$ (d), for $\theta_1 = \theta_2 = \theta_3 = 0.7$.

6. Acknowledgements

This work is supported by International Science Programme (ISP, Sweden) and AIRES Sud projet EPIMAT.

7. References

Balogun, O.; Hubbard, M. & De Vries, J. J. (1988). Automatic control of canal flow using linear quadratic regulator theory, *Journal of hydraulic engineering*, Vol. 114, No. 1, (1988), 75-102.

Bastin, G.; Bayen, A. M.; D'apice, C.; Litrico, X. & Piccoli, B. (2009). Open problems and research perspectives for irrigation channels, *Networks and Heterogenous Media*, Vol. 4, No. 2, (2009), 1-4.

Bastin, G.; Coron, J. M.; D'Andréa-Novel, B. (2009). On lyapunov stability of linearised Saint-Venant equations for a sloping channel, *Networks and Heterogenous Media*, Vol. 4, No. 2, (2009), 177-187.

Cen, L. H.; Xi, Y. G. (2009). Stability of Boundary Feedback Control Based on Weighted Lyapunov Function in Networks of Open Channels, *Acta Automatica Sinica*, Vol. 35, Issue. 1, (2009), 97-102.

Chen, M.; Georges, D. & Lefevre, L. (2002).Infinite dimensional LQ control of an open-channel hydraulic system, ASCC, Singapoure (2002).

De Halleux, J.; Prieur, C.; Coron, J. M.; D'Andréa-Novel, B. & Bastin, G. (2003) Boundary feedback control in networks of open channels, *Automatica*, Vol. 39, Issue. 8, (2003), 1365-1376.

De Saint-Venant, B. (1871)Théorie du mouvement non-permanent des eaux avec application aux crues des rivières et à l'introduction des marées dans leur lit, *Comptes Rendus Academie des Sciences*, Vol. 73, (1871), 148-154, 237-240.

Goudiaby, M. S.; Sene, A. & Kreiss, G. An algebraic approach for controlling star-like network of open canals, *preprint*.

Gowing, J. (1999), Limitations of water-control technology, *Agriculture Water Management*, Vol. 79, (1999), 95-99.

Leugering, G. & Georg Schmidt, E. J. P. (2002) On the modelling and stabilization of flows in networks of open canal, *SIAM J. Control Optim.*, Vol. 41, No 1, (2002), 164-180.

Leveque, R. J. (2002), *Finite Volume Methods for Hyperbolic Problems*, Cambridge Texts in Applied Mathematics, USA (2002).

T. Li, (2005) Exact boundary controlability of unsteady flows in a network of open canals, *Math. Nachr.*, Vol. 278, No 3, (2005), 278-289.

Litrico, X.; Fromion, V.; Baume, J. P. & Rijo, M. (2003) Modeling and PI control of an irrigation canal, *European Control Conference ECC* (2003), 6p.

Malaterre, P.0. (1998), PILOTE Linear quadratic optimal controller for irrigation canals, *Journal of irrigation and drainage engineering*, Vol. 124, No 4, (1998), 187-193.

Ndiaye, M. & Bastin, G. (2004), Commande fontiere adptative d'un bief de canal avec prélévements inconnus, *RS-JESA*, Vol. 38, (2004), 347-371.

E. F. Toro, *Riemann Solvers and Numerical Methods for Fluid Dynamics: A Practical Introduction* Springer-Verlag, Berlin (1999).

Weyer, E. (2003), LQ control of irrigation channel, *Decision and Control*, Vol. 1, (2003), 750-755.

Xu, C. Z. & Sallet, G. (1999) Proportional and integral regulation of irrigation canal systems governed by the Saint-Venant equation, *Proceedings of the 14th world congress IFAC*, pp. 147-152, Beijing, July 1999, Elsevier.

20

Spatial Variability of Field Microtopography and Its Influence on Irrigation Performance

Meijian Bai, Di Xu, Yinong Li and Shaohui Zhang
National Center of Efficient Irrigation Engineering and Technology Research, China Institute of Water Resources and Hydropower Research
China

1. Introduction

Surface irrigation is the main irrigation method,which is most widely used in the world.Surface irrigation performance is affected by field length,field width,field microtopography,inflow rate,soil infiltration,crops,and so on.Field microtopography is among the most important factors affecting the performance of basin irrigation system due to its influence on the advance and recession processes.It can direct the irrigation design and management to systematically analyze their effects on the basin irrigation performances by numerical simulation.

Field microtopography refers to the unevenness of a field surface,which may be characterized by a set of topographic data constituting the surface elevation differences (SED) between the actual and the target design elevations. The spatial variability of field microtopography includes a parameter characterizing the degree of unevenness and the spatial distribution of SED throughout the basin surface. The standard deviation (S_d) of SED is often used as an indicator of the degree of unevenness (Pereira and Trout 1999; Xu et al. 2002). However, for a same S_d the spatial distribution of SED may vary, which makes it difficult to describe the microtopography using a single indicator. Moreover, that single parameter does not allow to fully assessing the impacts of microtopography on the basin irrigation performances.

Because field-measured data are often limited and simulation modeling of surface irrigation is quite complex (*e.g.*, Walker and Skogerboe 1987; Strelkoff et al. 2000), studies on the influence of the microtopography on irrigation performances generally do not assume the spatial variability of SED, *e.g.*, Pereira et al. (2007). In fact, considering that spatial variability in modeling very much increases its complexity. However, not assuming the spatial variability of SED may lead to do not achieving an optimal solution for design and management of a basin irrigation system. Clemmens et al. (1999) and Li et al. (2001) generated basin surface elevations using a Monte-Carlo method basing upon the statistical characteristics of the surface elevation but they assumed that SED were random distributed inside a basin and did not consider its spatial variability.

Zapata and Playán (2000a) found that the spatial variability of surface elevations had much more influence on basin irrigation performance than the spatial variability of infiltration.

More attention should therefore be paid to the spatial variability of microtopography in basin irrigation design and evaluation to better support management and the decision making process relative to the target quality of precision leveling.

Considering the existing practical limitations in field microtopography characterization and in describing the impacts of the spatial variability of SED on basin irrigation performance, and aiming at supporting the improvement of basin irrigation systems in China, including the implementation of precision leveling, this study mainly comprises: (1) analyzing the semivariograms of SED for different basin types and the estimation of the semivariogram parameters from basin geometry parameters and the standard deviation of SED aiming at understanding the spatial dependence of surface elevations; (2) developing a stochastic model, adopting Monte-Carlo generation and kriging interpolation techniques, to generate SED data when knowing the respective standard deviation; (3) evaluating the influence of spatial variability of field microtopography on irrigation performance by numerical simulation.

2. Spatial variability of field microtopography

Based on the measured surface elevation data the spatial variability of field microtopography was analyzed using geostatistical technique.

2.1 Surface elevation difference (SED*)*

The surface elevation difference (SED) is defined as the difference between the observed and the target design elevations at each grid point *i* (z_i, cm), thus:

$$z_i = H_i - \overline{H_i} \tag{1}$$

where H_i is the observed elevation (cm) and $\overline{H_i}$ is the target design elevation(cm) at the same point i (i = 1, 2, …, n). The degree of unevenness of SED is characterized by the standard deviation (S_d) of the z_i values:

$$S_d = \sqrt{\frac{\sum_{i=1}^{n}\left(z_i - \bar{z}\right)^2}{n-1}} \tag{2}$$

where $\bar{z}$ is the mean of SED (cm) observed in *n* grid points.

2.2 Geostatistics

The spatial variability of basin SED was analyzed using geostatistical techniques (Clark 1979). Experimental semivariograms $\gamma(h)$ were applied. These express the relation between the semivariance of the sample and the sampling distances:

$$\gamma(h) = \frac{1}{2N}\sum_{i=1}^{N}\left[z(x_i) - z(x_i + h)\right]^2 \tag{3}$$

where x_i is the coordinate of the observation point i; $z(x_i)$ is the respective SED value (m), h is the distance between pairs of observations (m), and N is the number of data pairs. The semivariograms models are defined with three parameters: the nugget (C_0), the sill (C_0+C), and the range (R). The nugget is the value of the semivariogram for a distance equal to zero. A non-null nugget may indicate either a systematic measurement error, or that a spatial variation occurs at a scale smaller than that used for measurements. The sill is the final stable value of the semivariogram. The range is the distance at which the semivariance reaches that stable value. As discussed by Barnes (1991), when the sample values are evenly distributed over an areal extent many times larger than the range of the variogram, then the sample variance is a reasonable first estimate for the variogram sill. When different conditions occur, the sample variance may, on the average, significantly underestimate the variogram sill. However, comparing the sample variance and the sill may be a good criterion for testing the validity of adopting a given experimental variogram model because if sill and variance differ greatly the experimental model is suspect (Barnes 1991).

The indicative goodness of fit (IGF) (Pannatier 1996) was adopted to quantify the fitting error when a theoretical semivariogram is adjusted to experimental data. The selected theoretical semivariogram is the one that produces minimal differences between observed and computed values. The IGF is given by

$$IGF = \sum_{i=0}^{n} \frac{P(i)}{\sum_{j=0}^{n} P(j)} \cdot \frac{D}{d'(i)} \cdot \left[\frac{\gamma(i) - \hat{\gamma}(i)}{\sigma^2} \right]^2 \quad (4)$$

where n is the number of lags, D is the maximum distance of lags, $P(i)$ is the number of pairs for lag i, $d'(i)$ is the distance for lag i; $\gamma(h)$ is the empirical semi-variogram for lag i; $\hat{\gamma}(i)$ is the theoretical semi-variogram for lag i; and σ is the standard deviation of analyzed data.

2.3 Basic data

Field-measured SED data were obtained through surveying of 116 basins located at Daxing and Changping in Beijing region, Xiongxian in Hebei Province, and Bojili in Shandong Province. Basin SED from Changping, Xiongxian and Bojili were observed using a topographic level with an accuracy of 1 mm at intervals of 5 to 10 m. The basin SED from Daxing was observed using both a topographic level and a GPS at intervals of 1.5 to 10 m; the accuracy of GPS was about 5 mm.

The observed basins were classified relative to their forms into three types depending upon the basin length (L) and width (W): strip basin, when the ratio $L/W > 3$ with $W \leq 10$ m; narrow basin when $L/W > 3$ with $W > 10$ m, and wide basin when $L/W < 3$. Table 1 summarizes related data on basins length, width, standard deviation of SED and average longitudinal slopes. It can be seen that the basins observed cover a large range of basin lengths, generally larger for the narrow basins. Basin widths also cover a large range; they are generally smaller in strip basins and larger in wide ones. S_d tends to be larger when the length is longer. The average longitudinal slope S_o is generally positive but small, not far from zero.

Basin parameters	Strip basins		Narrow basins		Wide basins	
	Range of observations	mean	Range of observations	mean	Range of observations	mean
Length (m)	30~278	84	50~300	158	20~200	93
Width (m)	1.9~10.0	4.9	10.0~35	19.0	10.0~80.0	51.0
S_d (cm)	0.80~4.50	1.93	1.20~5.30	3.11	1.50~4.00	2.53
Slope (‰)	0.1~4.3	1.0	0.0~3.6	0.9	0.0~3.3	1.1

Table 1. Main basin size and microtopographic parameters relative to the three basin types

2.4 Spatial structure of SED

The spatial structure of SED was analyzed using geostatistical techniques (see Section 2.2). Spherical semivariograms were fitted to the 116 observed basins. The descriptive statistics of the semivariogram parameters relative to the three basin types are presented in Table 2. Results show that the nugget is generally smaller for the strip basins and larger for the narrow ones. This may indicate that for narrow basins a spatial variation may occur at a scale smaller than that used for observations. The sill is also larger for the same basins. The range is not very different among the three types of basins and is larger when the basin length is longer. The ratio $C_0 / (C_0+C)$ averages 0.21, 0.34 and 0.32 respectively for strip, narrow and wide basins; these values indicate that a medium to strong spatial correlation exists for SED.

Three typical experimental semivariograms of SED having low, medium and high IGF are presented in Fig. 1. They refer to strip basins whose sizes are 30 × 6, 67× 2.5 and 82 × 7.5 m, respectively. They concern a spherical theoretical semivariogram, which is the one that best fitted the experimental data.

Basin type	Statistics	Semivariogram parameters				IGF
		Nugget (C_0) (cm²)	Sill (C_0+C) (cm²)	C_0/(C_0+C)	Range (R) (m)	
Strip basins	Maximum	2.20	22.00	0.67	60.00	0.097
	Minimum	0.00	0.80	0.00	5.00	0.02
	Mean	0.58	4.66	0.21	16.69	0.026
	Variance	0.52	0.47	0.27	0.47	0.60
Narrow basins	Maximum	8.0	29.00	0.67	58.00	0.071
	Minimum	0.00	1.45	0.00	6.00	0.003
	Mean	2.95	10.56	0.34	19.91	0.009
	Variance	0.63	0.62	0.64	0.54	0.49
Wide basins	Maximum	5.00	15.40	0.63	65.00	0.078
	Minimum	0.00	2.15	0.00	4.00	0.003
	Mean	1.92	6.89	0.32	25.83	0.012
	Variance	0.75	0.53	0.56	0.67	0.53

Table 2. Statistics of semivariogram parameters of SED for three basin types

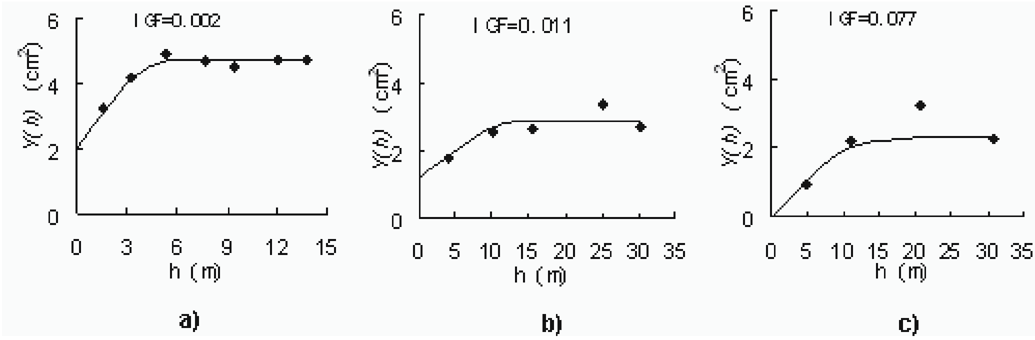


Fig. 1. The Experimental and Theoretical Semivariogram of SED for Different IGF

2.5 Calculation of the semivariogram parameters of SED

To search for the relationships among basin parameters and the parameters of SED semivariograms linear regressions were applied between every pair of parameters. Table 3 shows the correlation coefficients obtained and their significance level. Results show that the range mainly depends upon the basin length (*L)* and area (*A*), as well as on the observation distances (*d*). *R* also depends on the width (*W*) except for the strip basins which have a small *W*. The nugget is negatively correlated with the distance among observation points and shows relatively low correlation with the basin parameters; however, some significant relationship exists with the area and the length of the basins. The sill, as discussed before, is close to the variance of SED (S_d^2). The latter also relates to the range, mainly for the narrow basins. Based upon the relationships among basin parameters (L, A, S_d) and semivariogram parameters (C_0, C_0+C, R) empirical regression equations were established for the three types of basins (Table 4), which will be used for the developing of the stochastic modeling of field microtopography,for adjusting the generated SED in terms of spatial dependence of their values.

Basin type	Basin parameters	Nugget C_0	Sill C_0+C	Ratio $C_0/(C_0+C)$	Range R
Strip basins	L	-0.29	0.40**	-0.30	0.98**
	W	-0.28	0.21	-0.36*	0.05
	A	-0.34*	0.42**	-0.38*	0.90**
	S_d	-0.16	0.98**	-0.35*	0.39*
	d	-0.59*	0.31*	-0.39*	0.78**
Narrow basins	L	0.26	0.56**	-0.01	0.84**
	W	0.19	0.54**	-0.18	0.50**
	A	0.11	0.63**	-0.19	0.72**
	S_d	0.13	0.94**	-0.33	0.65**
	d	-0.69**	0.34*	-0.54**	0.67**
Wide basins	L	0.33*	0.21	0.05	0.89**
	W	0.25	0.22	0.01	0.91*
	A	0.24	0.16	0.01	0.93**
	S_d	0.17	0.93**	-0.43**	0.35*
	d	-0.70**	0.21	-0.31	0.87**

Note: * significance level 0.05; ** Significance level 0.01L - length, W - width; A - area; S_d - standard deviation of SED; d - observation distances

Table 3. Coefficients of correlation relative to linear regressions between selected basin parameters and the parameters of the SED semivariograms for different basin types

Basin type	semivariogram parameters of SED		
	Nugget C_0 (cm²)	Sill (C_0+C) (cm²)	Range R (m)
Strip basin	$0.21S_d^2$	S_d^2	$0.18L+1.53$
Narrow basin	$0.34S_d^2$	S_d^2	$0.21L-4.11$
Wide basin	$0.32S_d^2$	S_d^2	$16.69A+5.26$

S_d^2 – variance of SED; L – basin length; A – basin area

Table 4. Empirical equations relating the parameters of the SED semivariograms with the basin characteristics for the three basin types

3. Stochastic modeling of field microtopography

3.1 Stochastic generation of SED

Considering both the randomness and the spatial dependence of basin SED values, the Monte-Carlo (M-C) method and kriging interpolation techniques were combined to develop a procedure for modeling microtopography. It consists of four steps:

1.*Stochastic generation of SED using the M-C method.* Based on the basins geometry (length L and width W), on the statistical characteristics of observed SED (mean $\overline{z}$ and standard deviation S_d), and on the observations grid spacings between rows (Δy) and columns (Δx), it is first determined the number n of elevation nodes to be randomly generated. Then n evenly distributed random numbers r_i [0, 1] are generated. The SED values z_i^0 corresponding to each r_i are computed through the following distribution:

$$F(z) = \int_{-\infty}^{z} \frac{1}{S_d\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{z-\overline{z}}{S_d}\right)^2\right] d_z \tag{5}$$

where variables are those defined above. It results a set of generated SED values z_i^0 for all the grid nodes i.

2.*Adjusting the generated SED to the expected range of values.* In theory, the SED may assume any value but in practice their range is limited and depends upon the mean $\overline{z}$ and the standard deviation S_d that characterize each field. It was empirically assumed that the generated SED should fall within the interval [$\overline{z}$ -3S_d, $\overline{z}$ +3S_d]. Therefore, when any value z_i^0 is out of this range another value is generated using the M-C method.

3.*Establishing a spatial dependence for the generated SED values.* The generated SED values produce a spatial distribution different from the one of the actual microtopography that may be unrealistic because the proximity microtopographic relations between neighbor points are not considered. A kriging interpolation is then used to establish a spatial dependence of the generated SED values that considers the observed spatial structure of SED; New values for SED at each point i, z_i^1, are therefore estimated from the SED values at the neighbor points around i but assuming the above defined range of variation. Thus, the z_i^0 values are replaced by z_i^1 according to the relation

$$Z(z_i^1) = \sum_{j=1}^{M} \lambda_j (z_j^0) \tag{6}$$

where M is the number of points surrounding the point i, and λ_j are the weighing coefficients relative to the j neighbour points whose SED values are Z_j^0.

4.Adjusting the generated SED for maintaining the original statistical characteristics. The generation and adjustment procedures referred above cause that the statistical characteristics of SED are changed relative to the initial mean $\bar{z}$ and standard deviation S_d. Therefore, it is required to correct the generated SED aiming at assuring that their mean and standard deviation are conserved. First they are corrected for the mean and, afterwards, for the standard deviation, respectively:

$$z_i^2 = \frac{\bar{z}}{\bar{z}_1} z_i^1 \tag{7}$$

$$z_i^3 = (z_i^2 - \bar{z}) \frac{S_d}{S_{d2}} + \bar{z} \tag{8}$$

where z_i^2 and z_i^3 are the values for SED after the respective corrections for the mean and the standard deviation, $\bar{z}_1$ is the mean of the z_i^1 values resulting from the kriging adjustment, and S_{d2} is the standard deviation of z_i^2 values.

3.2 Determining the number of SED generations

When SED are generated using the described stochastic modeling procedure, more than one set of SED can be generated for a given S_d. Different sets of SED generated with the same S_d will produce different values for the irrigation performance indicators when keeping constant all other factors that influence advance and recession. *i.e.,* the irrigation performance relative to a given SED set is unique. Thus, it is necessary to determine how many SED sets need to be generated for a given S_d to appropriately analyze the impacts of the spatial variability of the basin's microtopography on the irrigation performance.

3.2.1 Theoretical method

The number of SED generations can be determined by analyzing the trend of change of selected irrigation performance indicators resulting from the simulation of a given irrigation event through a number of SED sets. When N sets are generated for a given S_d then N sets of irrigation performance indicators are obtained by simulation of the same irrigation event. The number m ($m < N$) of SED generations required to characterize the population of basin SED may then be determined by analyzing the changes on irrigation performance with the number of SED generations.

Considering the population of an independent random variable X normally distributed with mean μ and variance σ^2, if X_1, X_2, …, X_m is a sample of size m from that population and whose mean is $\bar{X}$, then the probability for any value X_j (j = 1, 2, …, m) to be included in the confidence interval of probability 1-α, is

$$P\left\{ \left| \frac{\bar{X} - \mu}{\sigma / \sqrt{m}} \right| < Z_{\alpha/2} \right\} = 1 - \alpha \tag{9}$$

where $Z_{\alpha/2}$ is the value of the standard normal distribution corresponding to the probability $\alpha/2$. Therefore, the interval of estimation of the variables X_j (j = 1, 2, …, m) relative to the same probability is $\left[\overline{X}-\frac{\sigma}{\sqrt{m}}Z_{\alpha/2},\overline{X}+\frac{\sigma}{\sqrt{m}}Z_{\alpha/2}\right]$ (Mood et al. 1974; Deng 2002). Consequently, when aiming at an estimation precision l_0, the sample size required m shall satisfy the condition $\sigma\cdot Z_{\alpha/2}/\sqrt{m}\ \le l_0$; thus, the number of SED generations, *i.e.*, the sample size, should be at least

$$m=(\sigma\frac{Z_{\alpha/2}}{l_0})^2 \tag{10}$$

3.2.2 numerical experiment

A numerical experiment was developed to assess the number of sets of generated SED values for each basin type and S_d aiming at representing the possible land surface conditions to be analyzed through simulation for assessing the impacts of spatial variability of microtopography on basin irrigation performance.

Basin size and S_d were considered in numerical experiments to decide the number of SED generations. Data in Table 1 led to adopt as typical basin sizes 100 × 5 m, 150 × 20 m and 100 × 50 m respectively for the strip, narrow and wide basin types. For these typified basins, six degrees of surface unevenness are considered with S_d of 1, 2, 3, 4, 5, and 6 cm. Therefore, eighteen basin conditions resulted from combining those 3 basin sizes and the 6 S_d values. For each basin condition, 200 sets of SED were generated, thus producing 200 sets of irrigation performance indicators (water application efficiency (E_a),distribution uniformity(DU_{lq}) and average irrigation depth corresponding to the water justly cover the entire basin surface (Z_{adv})). In these simulations with the irrigation model B2D , the same soil infiltration parameters, Manning's hydraulics roughness n_r, soil water content when the irrigation starts and inflow rate conditions were adopted. The values for the Kostiakov-Lewis infiltration parameters and the Manning's roughness coefficient n_r were those obtained from a field experiment in a loamy soil in North China (k = 0.0045 m.min^{-a}, a = 0.46, f_0 = 0.0003 m.min^{-1}, n_r = 0.1 s.m$^{-1/3}$). The unit width inflow rate adopted was q = 4 l.s^{-1}.m^{-1}. The water cut-off time adopted was that required for the advance to be completed as practiced in North China, thus assuring that infiltration Z > 0 in any point of the basin. The computational grid adopted was 1 × 1 m, 2 × 2 m and 5 × 5 m respectively for strip, narrow and wide basin types.

3.2.3 Setting the number of SED generations required for each basin type and S_d

Fig. 2 and Fig. 3, relative to a typical narrow basin, show results on the variation of the mean and the standard deviation of the performance indicators Z_{adv}, E_a and DU_{lq} with the number of SED generations (sample size). Results show that the mean and standard deviation of Z_{adv}, E_a and DU_{lq} do not change after a given threshold number of generations is reached, which depends upon S_d. Results for the wide and strip basins (not shown) are similar.

The mean values of the indicators Z_{adv}, E_a and DU_{lq} become nearly constant for a smaller number of generations than the respective standard deviation as shown in Figs. 2 and 3. Thus, the threshold number was computed from the latter, when the relative differences among six consecutive standard deviation values become smaller than 5%. The resulting values for the standard deviation of the referred indictors when they could be considered unchanged despite the number of generations increase are presented in Table 5 for the 3 basin types. Results show that those standard deviations are the smallest when S_d = 1 cm and increase with S_d. Greater changes occur for the strip basins because the length/width ratio is larger, which relate to its great influence on the advance process.

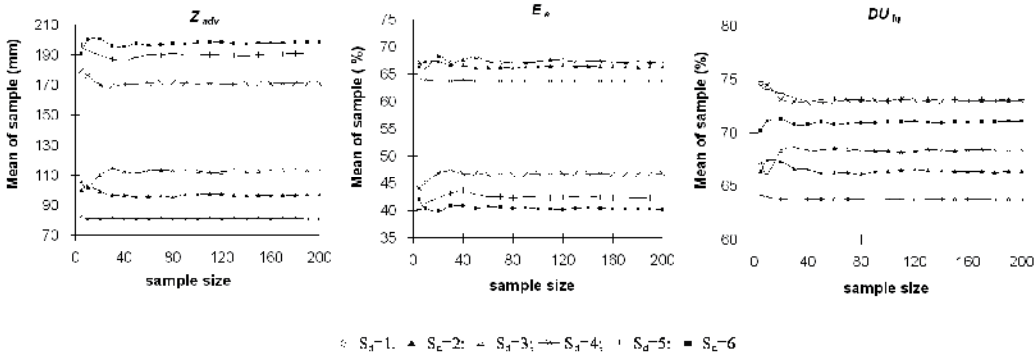


Fig. 2. Variation of the mean of the performance indicators Z_{adv}, E_a and DU_{lq} with the sample size (number of generated SED) for a typical narrow basin

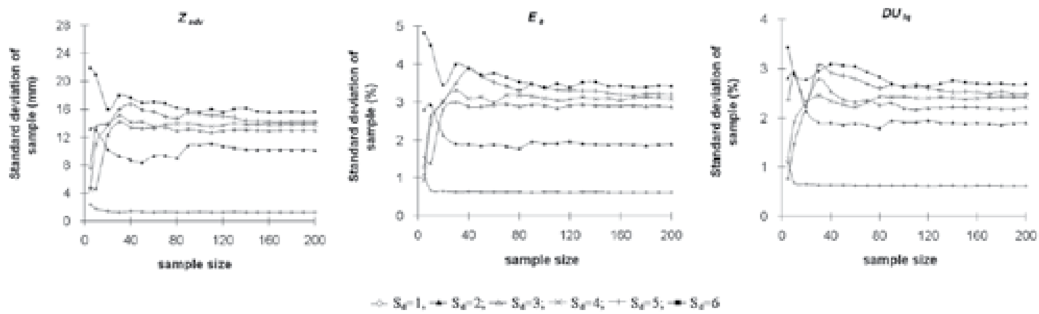


Fig. 3. Variation of the standard deviation of the performance indicators Z_{adv}, E_a and the DU_{lq} with the sample size (number of generated SED) for a typical narrow basin

Basin type	Performance indicator*	S_d=1 cm	S_d=2 cm	S_d=3 cm	S_d=4 cm	S_d=5 cm	S_d=6 cm
Strip basin	Z_{adv} (mm)	0.80	6.34	11.30	13.50	15.81	18.70
	E_a (%)	0.18	2.00	3.50	3.69	3.80	4.11
	DU_{lq} (%)	0.65	2.90	3.10	3.50	3.70	3.80
Narrow basin	Z_{adv} (mm)	1.26	10.21	13.01	13.80	14.23	15.59
	E_a (%)	0.62	1.89	2.90	3.10	3.20	3.42
	DU_{lq} (%)	0.62	1.89	2.21	2.40	2.50	2.69
Wide basin	Z_{adv}(mm)	1.05	8.44	10.25	12.37	15.37	17.02
	E_a (%)	0.66	2.56	2.81	3.00	3.42	3.56
	DU_{lq} (%)	0.65	2.35	2.49	2.79	2.87	3.06

* DU_{lq} - distribution uniformity, E_a – application efficiency, and Z_{adv} – infiltrated depth when the advance is completed

Table 5. Standard deviation of the irrigation performance indicators when their values become stable after simulating an irrigation event with a number of SED generations for various standard deviation (S_d) values .

The minimum number m of generations required for each basin type and various S_d values was computed with Equation 10 using variance data from simulations (Table 5). In this application the target precision l_0 are 3mm, 1% and 1% respectively for Z_{adv}, E_a and DU_{lq}, and the confidence level is associated with the probability $\alpha = 0.05$. Results for m are given in Table 6 showing that m increases with S_d, and are larger for Z_{adv} and smaller for DU_{lq}. Therefore, the number of generations adopted depends upon the indicator that is considered more important for the analysis. Because DU_{lq} is the best indicator of the system performance (Pereira et al. 2002), generally it is enough to consider the m values relative to this indicator. Otherwise, as for this study that pretends a wider analysis, the larger m value is selected, *e.g.*, 33 SED generations would be required for the strip basin when S_d = 2 cm, and 55 when S_d = 3 cm.

Basin type	Performance Indicator*	Precision l_0	Number of SED generations					
			S_d = 1 cm	S_d = 2 cm	S_d = 3 cm	S_d = 4 cm	S_d = 5 cm	S_d = 6 cm
Strip basin	Z_{adv}	3 mm	1	18	55	78	107	150
	E_a	1%	1	16	48	53	56	65
	DU_{lq}	1%	1	33	37	48	53	56
Narrow basin	Z_{adv}	3 mm	1	45	73	82	87	104
	E_a	1%	1	14	33	38	40	45
	DU_{lq}	1%	1	14	19	23	24	28
Wide basin	Z_{adv}	3 mm	1	31	45	66	101	124
	E_a	1%	1	26	31	35	45	49
	DU_{lq}	1%	1	22	24	31	32	37

* DU_{lq} - distribution uniformity, E_a – application efficiency, and Z_{adv} – infiltrated depth when the advance is completed

Table 6. Number of SED generations required for various standard deviation (S_d) values and basin types

3.3 Model validation

3.3.1 Field experiments for testing and validation of the stochastic model

Irrigation experiments were developed in a small level basin (30×15 m) located in the Experiment Station of the National Center of Efficient Irrigation Engineering and Technology Research, at Daxing, south of Beijing in the North China Plain. The soil was kept bare for easiness of observations. The soil texture is sandy loam and the average soil water content at field capacity and wilting point are respectively 0.26 and 0.10 $m^3 m^{-3}$. The basin was laser-controlled leveled. The observed standard deviation of SED is S_d = 1.8 cm.

The irrigation management followed the standard practice of winter wheat irrigation in this area. Different modes of water application into the basins were adopted: (1) fan inflow for the first irrigation, with the inflow point located by the middle of the upstream end of the basin; (2) corner inflow for the second irrigation, with the inflow concentrated at the upstream left corner of the basin; and (3) line inflow at the third irrigation, with water application at points distant 1 m along the upstream end of the basin. The water was conveyed to the field by a PVC pipe from the well pump where discharge was measured with a 1010WP-1/1010N supersonic flow meter. The average inflow rate was 12 l .s^{-1} for all irrigations. The water application was cut-off when the irrigation water covered the entire basin, i.e., the advance was completed.

A 1.5 ×1.5 m grid was used to perform all observations of soil surface elevation, and advance and recession times (Fig. 4). 12 measurement points were selected to obtain the cumulative infiltration curves before the first and second irrigation events (Fig. 4).

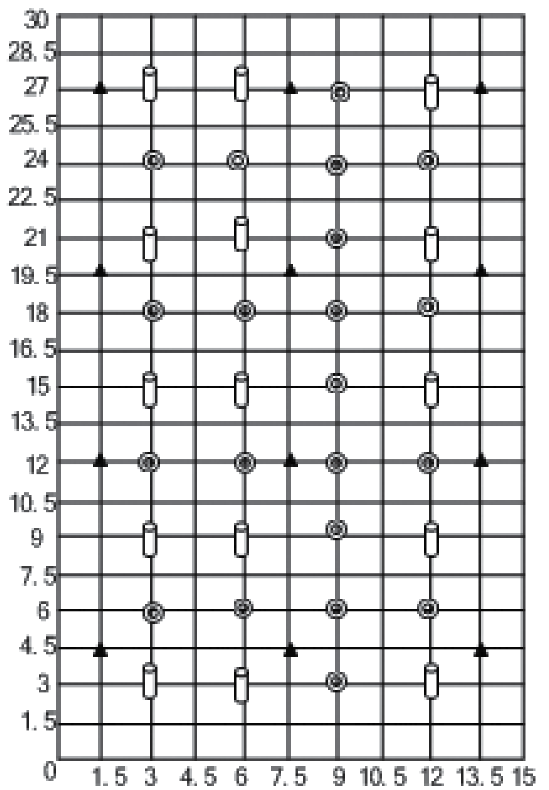


Fig. 4. Field measurements grid in the test basin: + advance and recession,surface elevation; ⊖ surface water depth; ⊖ and ◎ soil water content; ▲ soil infiltration.

The soil water content was observed one day before and after the irrigation to assess both the soil water deficit before irrigation and the infiltrated depth after it. Results were used to evaluate the irrigation performance. The soil water content was measured with a Time-Domain Reflectometry system type HH2 at 10, 20, 30, 40, 60 and 100 cm depth. Measurements were carried out at 36 grid points, i.e., adopting a 3 ×3 m grid (Fig. 4).

The surface water depth was measured using the water depth measuring device described by Li et al. (2006). This device is able to automatically measure and record the variation of water depth at given points during the whole duration of an irrigation event. Its testing results show that the adopted sensor is sensitive to the dynamic variations of the water depth with a precision of ±5 mm (Li et al. 2006). The water depth measuring devices were placed at every observation point before the irrigation starts and the recorded data was transferred to a computer after it ends. The measuring grid adopted is 6 × 6 or 6 × 3 m as described in Fig. 4.

3.3.2 Assessment indicators of model fitting

To assess the stochastic generation of SED, the irrigation model B2D was applied with both observed and generated SED data. Comparisons are made relative to the model computed irrigation performances. The average absolute error (AAE) and the average relative error (ARE) are used to assess the precision of simulations. These indicators are defined as:

$$AAE = \frac{1}{n}\sum_{i=1}^{n}\left|O_i - S_i\right| \tag{11}$$

$$ARE = \frac{100}{n}\sum_{i=1}^{n}\frac{\left|O_i - S_i\right|}{O_i} \tag{12}$$

where O_i and S_i are the values for the variables observed or simulated respectively, and n is the number of the observation points for the variables referred above. The subscripts OBS and GEN are used with these indicators when they result from simulations performed with measured and generated data, respectively.

3.3.3 results of model validation

The main observation data relative to the three irrigation events is summarized in Table 7. It can be observed that the first irrigation smoothed the basin surface, with S_d decreasing from 1.77 cm at the first event to 1.56 cm at the second one. Results show that adopting the traditional management, cutting-off the water application when the advance is completed, originates a non-uniform water application with very large differences between the maximum and minimum infiltration depths, 70 mm for the first event. Hence, the standard deviation of the infiltration depths (SD_Z) is large, 18 mm for that event. These non-uniformities produce low DU_{lq}.

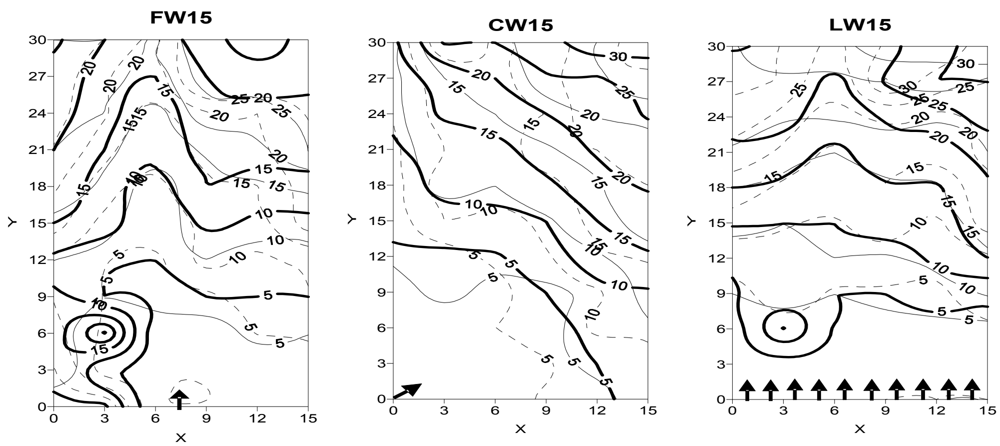
Irrigation data (day/month)	SED Average (cm)	S_d (cm)	Inflow rate ($l \cdot s^{-1} \cdot m^{-1}$)	Irrigation time (min)	Infiltration depth Z(mm) Max.	Min.	Average	Z_{lq}	SD_Z	Inflow type
26/11	5.09	1.77	0.8	41.3	103	33	66	46	18	Fan
15/4	4.76	1.56	0.8	38.1	84	36	61	44	13	Corner
20/5	4.93	1.57	0.8	40.0	92	28	64	37	15	Line

S_d – standard deviation of SED; SD_Z - standard deviation of infiltrated depths

Table 7. Selected results of irrigation experiments with different inflow types

Considering the basin size and the observed S_d, and taking into consideration the results in Table 6 when the analysis focus on all the indicators, 31 SED generations were performed for each observed S_d. The three irrigation events were then simulated with observed and generated SED data using the B2D model. The computational grid was 1.5 × 1.5 m; the infiltration data used were those observed in field experiments and the Manning's roughness coefficient was n_r = 0.1 s.m$^{-1/3}$ as indicated by Liu et al. (2003) for similar bare soil conditions. The resulting irrigation performance indicators (DU_{lq} and Z_{adv}) and advance time were used to compare the simulation results when observed or generated SED data (31 SED data sets) were input to the irrigation model.

Fig. 5 presents the advance curves observed and simulated with 5 minutes time steps referring to the 3 irrigation events, each one with a different inflow type (fan, corner and line). The simulated curves represented correspond to using as input the measured SED and a generated SED set which values are close to the average values.



a) Fan inflow b) Corner inflow c) Line inflow

Fig. 5. Advance curves observed (- - -) and simulated using measured SED (**—**) and generated SED data (—) with a time step of 5 minutes for a) fan inflow, b) corner inflow and c) line inflow.

The quality of these simulations is analyzed with the average absolute and relative errors (*AAE* and *ARE*) relative to all grid points for the case where observed SED are used, and the maximum, minimum and mean values of *AAE* and *ARE* relative to the 31 sets of generated SED (Table 8). The symbols OBS and GEN are used in this Table 8 to identify the simulations using observed and generated SED data.

Results show that differences between AAE_{OBS} and AAE_{GEN}, as well as between ARE_{OBS} and ARE_{GEN}, are small, *i.e.*, using generated SED data does not induce significant additional errors relative to using SED observed. However, the maximal errors are somewhat large but were infrequent. This means that using data generated with the same statistical characteristics as those observed in the field produce advance simulation results generally similar to those observed. Comparing the results relative to the three types of inflow into the basins (Table 8 and Fig. 5) it can be observed that line inflow is more accurately simulated by the B2D model than fan or corner inflow. Errors for the latter are the highest. This relates with the way how the water spreads from up- to downstream along the field and shows that when the inflow is concentrated the advance is more influenced by the microtopography of the basin surface. Results also show that the B2D model is an appropriate tool for 2-Dimension simulation of basins surface flow.

Inflow type	Irrigation event		AAE_{OBS} (min)	AAE_{GEN} (min)	ARE_{OBS} (%)	ARE_{GEN} (%)
Fan	1st	Mean	2.4	2.6	26.8	22.2
		Maximum		4.4		41.3
		Minimum		1.9		16.7
Corner	2nd	Mean	2.4	2.5	25.5	27.3
		Maximum		4.7		42.5
		Minimum		2.0		19.8
Line	3rd	Mean	1.9	1.7	18.7	13.8
		Maximum		3.8		35.1
		Minimum		1.4		12.6

Table 8. Average absolute and relative errors of estimation (*AAE* and *ARE*) of the advance time when simulations are performed with observed or generated SED

Table 9 presents the observed and simulated irrigation performances for fan, corner and line inflow. Because the irrigation cut-off was practiced when the advance is completed, for the three cases the distribution uniformity DU_{lq} is less good due to the small infiltrated depths downstream as shown in Table 7. Results are similar for the three inflow types. Table 10 presents the estimation errors for DU_{lq} and the infiltrated depth at time of cut-off, Z_{adv}. Data show that respective errors when using observed or generated SED data are similar and small, generally below 10%. Errors for the line inflow are smaller than for fan or corner inflow, which relates with results for advance referred before. Hence, it is possible to conclude that using various sets of generated SED data to analyze the impacts of basin microtopography on irrigation performances provides information similar to that derived from using observed SED values.

		Basin inflow type		
		Fan	Corner	Line
DU_{lq} (%)	From observations	70.1	72.6	57.9
	From measured SED data	64.1	65.3	60.1
	From generated SED data	62.9	65.3	62.1
Z_{adv} (mm)	From observations	66.0	61.0	64.0
	From measured SED data	69.2	63.5	62.8
	From generated SED data	63.0	57.4	60.7

* DU_{lq} - distribution uniformity, and Z_{adv} – infiltrated depth when the advance is completed

Table 9. Observed and simulated irrigation performance indicators using measured or generated SED data

Results above show that the stochastic modeling approach to generate the SED data allows a detailed study on impacts of microtopography on irrigation performance. Basin irrigation is applied in more than 95% of irrigated land in China, thus the improvement of these systems will have a great importance to overcome water scarcity and to provide for the sustainability of irrigated agriculture. As reported earlier, previous research has shown that land surface unevenness is a main factor contributing to low distribution uniformity and application efficiency in current basin irrigation systems. Various approaches are used for improving those systems including the use of modeling for design, such as the SIRMOD and SRFR models (Walker 1998; Strelkoff 1990) and the decision support system SADREG (Gonçalves and Pereira 2009). However, these models do not consider the effects of microtopography on the irrigation performance and it is advisable that their application follows a detailed study on such impacts that could provide for more realistic base assumptions for modeling. However, collecting field information on microtopography conditions is time and money consuming. Differently, adopting the approach developed in this study to generate a spatialized SED combined with the B2D model (Playán et al. 1994a, b) could be used to define the best improvement conditions for selected basin types predominant in various regions of China. Results for validation of the SED generation model shown above encourage its adoption in research practice oriented for surface irrigation improvement. This research is complemented with an evaluation of this modeling tool to assess the impacts of the spatial variability of mirotopography on the irrigation performance of various basins.

		Basin inflow type		
		Fan	Corner	Line
DU_{lq}	AAE_{OBS} (%)	6	7.3	2.2
	$Max\ AE_{GEN}$ (%)	10.6	10.6	6.1
	$Min\ AE_{GEN}$ (%)	3.8	4.6	2.9
	AAE_{GEN}(%)	7.2	7.3	4.2
	ARE_{OBS} (%)	8.5	10.1	3.8
	ARE_{GEN}(%)	9.5	9.4	5.3
Z_{adv}	AAE_{OBS} (mm)	3.2	2.5	1.2
	$Max\ AE_{GEN}$ (mm)	10	11	12
	$Min\ AE_{GEN}$ (mm)	0	0	0
	AAE_{GEN}(mm)	3	3.6	3.3
	ARE_{OBS} (%)	4.8	4.1	1.9
	ARE_{GEN}(%)	4.6	5.8	5.2

* DU_{lq} - distribution uniformity, and Z_{adv} – infiltrated depth when the advance is completed

Table 10. Absolute and relative errors of estimation (*AAE* and *ARE*) of the irrigation performance indicators when simulations are performed with observed or generated SED data

4. Influence of spatial variability of field microtopography on irrigation performances

4.1 Numerical experiments

Considering the statistical results relative to basin characteristics reported in Table 1 for 116 basins of North China, three representative basins were considered for the defined basin types strip, narrow and wide with sizes 100 × 5 m, 150 × 20 m and 100 × 50 m, respectively. For these basins, five degrees of surface unevenness were considered with S_d of 1, 2, 3, 4 and 5 cm. Two design slopes were adopted, S_o = 0.1% and zero leveled, as well as two inflow rates, q = 2 $L.s^{-1}.m^{-1}$ and q = 4 $L.s^{-1}.m^{-1}$. For each basin type and S_d, the number *m* of SED generated with the generation model of spatial variability of microtopography (SVM model) is indicated in Table 11. The irrigation simulation model B2D was used to simulate the irrigation process relative to every SED data set. The basin irrigation performances referred above were computed for every simulation.

	S_d = 1 cm	S_d = 2 cm	S_d = 3 cm	S_d = 4 cm	S_d = 5 cm
Strip type	1	33	55	78	107
Narrow type	1	45	73	82	87
Wide type	1	31	45	66	101

Table 11. Number *m* of SED generations for each S_d and basin type

For the simulations with B2D, the same soil infiltration parameters, Manning's roughness n_r, initial soil water content and inflow conditions were adopted. Infiltration was characterized using the Kostiakov-Lewis equation. The infiltration parameters (k, a, f_0) and the Manning's roughness n_r were the same obtained in the field test in North China Plain used to validate the SVM model (See section 3.3.1) i.e., k = 0.0045 $m.min^{-1}$, a = 0.46, f_0 = 0.0003 $m.min^{-1}$, and n_r = 0.1 $s.m^{-1/3}$. This infiltration corresponds to a silty soil, whose layers are sandy loam or silt loam, and the average soil water content at field capacity and wilting point are respectively 0.26 and 0.10 $m^3 .m^{-3}$. Other simulation characteristics are the following: (a) the inflow time was the minimum irrigation time ensuring that advance could be completed, thus ensuring that the infiltration depth is $Z > 0$ everywhere in the basin; (b) the net target irrigation depth was set as Z_{tg} = 80 mm; (c) the inflow inlet was supposed to be located by the middle of the upstream end of the basin. According to the basin size and the simulation precision adopted, the calculation grids were 1 × 1 m, 2 × 2 m and 5 × 5 m, respectively for the strip, narrow and wide basins.

4.2 Irrigation performance indicators

The distribution uniformity of the low quarter, DU_{lq}, was selected as performance indicator in this study. It was defined (Merriam and Keller 1978) as:

$$DU_{lq} = 100 \frac{Z_{lq}}{Z_{avg}} \quad (13)$$

where Z_{lq} is the average low quarter infiltrated depth (mm) and Z_{avg} is the average depth of water applied to the field (mm).

In addition, the ratio

$$R_Z = Z_{adv} / Z_{tg} \quad (14)$$

between the average depth of water infiltrated following the complete advance criterion, Z_{adv}, (mm) and the net target irrigation depth, Z_{tg}, (mm) was used to assess the irrigation performance computed with the B2D model when simulating the irrigation events for the various SED generated sets. $R_Z > 1.0$ when overirrigation occurs, and $R_Z < 1.0$ when there is underirrigation. This indicator is used instead of the application efficiency because the latter is a management indicator that not only depends upon the variables characterizing the irrigation system but also upon the irrigator decisions, mainly referring to the timing of irrigation, that relates to the available soil water, and the depth applied, that determines the occurrence of deep percolation at a given irrigation event (Pereira 1999). Differently, R_Z indicates how the irrigation system is able to apply the target depth when influenced by land surface microtopography when the irrigation timing is appropriate. Z_{adv} was selected for the numerator of the ratio R_Z because Chinese farmers use to cut the inflow to the basins when the advance is to be completed, thus Z_{adv} indicates the expected infiltration when irrigation is managed that way.

4.3 Results and discussion

To characterize the influence of the spatial variability of microtopography on irrigation performance, simulations were performed for various S_d values (from 1 to 5 cm) and generating the number of variable SED referred in Table 11. Results in Fig. 6 show that infiltration at completion of advance, Z_{adv}, increases with S_d and, on the contrary, DU_{lq} decreases when S_d increases for zero-leveled basins (S_o = 0) but is insensitive to S_d for sloping basins (S_o =0.1%).

In sloping strip basins, when S_d increases from 1 to 5 cm, the average Z_{adv} increases from values close to the target Z_{tg} = 80 mm to values about 60% higher (Fig.6). If a zero leveled basin is considered, the average Z_{adv} becomes 80% higher, i.e. poorly leveled basins ($S_d \geq 4$ cm) .produce large overirrigation, mainly when no sloping. This reflects the role of the slope when the basin surface is uneven: advance is completed faster than for zero leveling. This also explains why farmers often adopted a mild slope and did not like to adopt zero leveling when improvements in surface irrigation were proposed (Cai et al. 1998). For these strip basins with slope, the average DU_{lq} shows little dependence on S_d but DU_{lq} increases when S_d decreases for zero leveled basins. The insensitiveness of sloping basins to S_d may be related to the fact that water keeps moving downwards after the advance is completed and is stored in the micro-depressions located downstream; therefore, infiltration is higher downstream, resulting that DU_{lq} in sloping strip basins cannot be high. In fact, it is limited to about 70%, thus indicating that an excellent performance is not achievable. Differently, for zero leveled basins a very high DU_{lq} is predicted when land leveling is excellent (S_d = 1 cm): 90% when the inflow rate is 4 L.s^{-1}.m^{-1}, and 86% when q = 2 L.s^{-1}.m^{-1}. These values progressively decrease when S_d increases; when S_d = 5 cm, DU_{lq} values are similar for zero leveled and sloping strip basins, near 70%.

For sloping narrow basins, the average Z_{adv} increases more than for strip basins when S_d = 5 cm and q = 2 L.s^{-1}.m^{-1}; for zero leveled basins and the same S_d and q, the average Z_{adv} increases to 186 mm, thus indicating an extremely high overirrigation. These differences in Z_{adv} relative to the strip basins are mainly due to the differences in length (100 vs. 150 m, respectively for the strip and narrow basins). Like for the strip basins, DU_{lq} is limited to about 74% and shows no sensitivity to changes in S_d, confirming that an excellent performance is not achievable with sloping basins. Differently, for zero leveled basins, very high average DU_{lq}, close to 90%, is predicted when leveling is excellent (S_d = 1 cm). For large S_d it results an average DU_{lq} close to that for sloping basins.

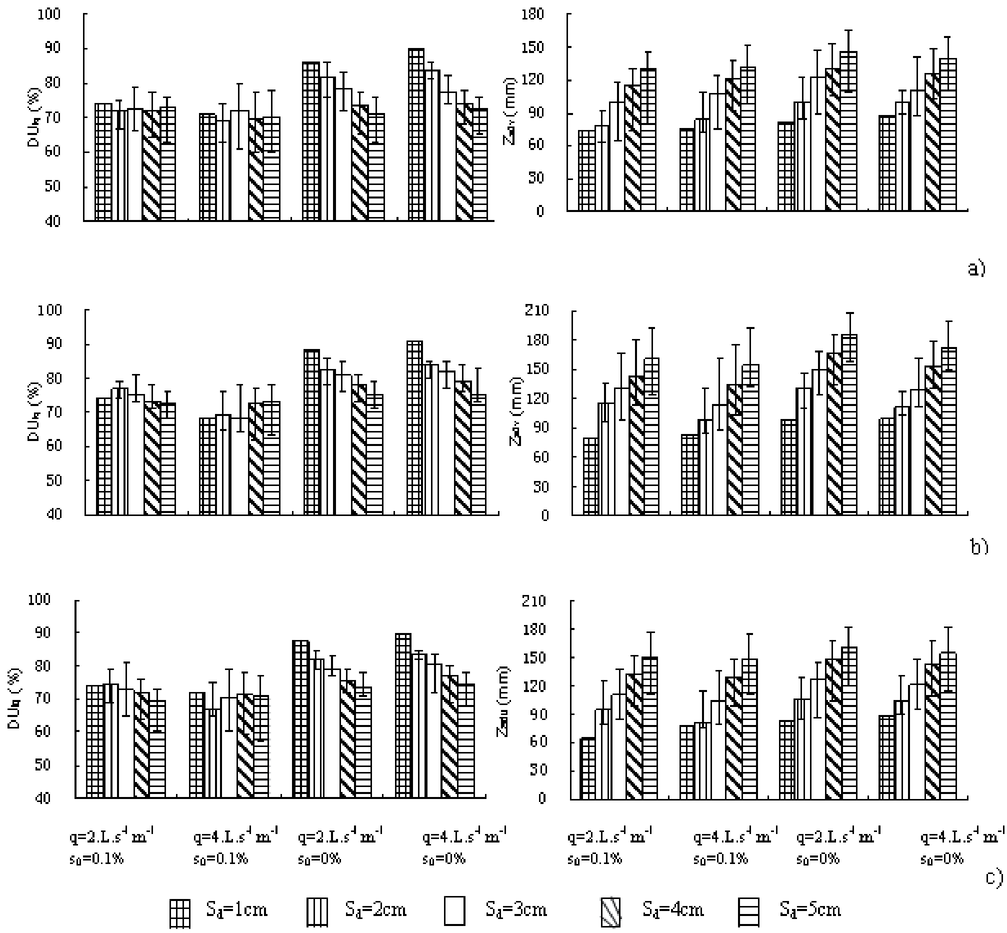


Fig. 6. Variability of the distribution uniformity DU_{lq}, and the infiltrated depth when the advance is completed Z_{adv}, as influenced by the microtopography (S_d varying from 1 to 5 cm) for basins with zero and 0.1% slope, and inflow discharges of 2 and 4 L s^{-1} .m^{-1}: a) strip, b) narrow, and c) wide basins (vertical bars indicate the range of variation for each case, the number of cases being that in Table 11)

For non-leveled (S_d = 5 cm) wide basins, the average Z_{adv} is 150 mm for q = 2 L.s^{-1}.m^{-1} and S_o = 0.1%, increasing to 162 mm when the slope is zero and adopting the same inflow discharge. For precision level basins and q = 2 L.s^{-1}.m^{-1}, the average Z_{adv} is much lower, 65 mm when S_o = 0.1% and 84 mm for zero leveling. These results are close to those for the strip basins; however Z_{adv} tends to be smaller for the latter. Differences to narrow basins relate to the large basin length of these ones, which produce a slower advance. Results for DU_{lq} are generally not far from those of strip basins. When S_o = 0.1% the average DU_{lq} is close to 72% and shows little dependence on S_d; for precision zero leveling DU_{lq} is close to 90% but decreasing to 74% when S_d = 5 cm.

Results above indicate that to achieve a high DU_{lq} zero leveling is required, preferably with a large inflow rate. When precise leveling is not applicable and water saving is intended, then a sloping surface is probably better for strip and narrow basins. If water saving is a priority, i.e., reducing Z_{adv}, it is required to adopt land leveling and a cutoff time smaller than the advance time. These results confirm those formerly obtained for strip basins in the North China Plain (Li and Calejo 1998) and long narrow basins in the lower reaches of the Yellow River (Fabião et al. 2003). Results for wide basins also identify the need for appropriate land leveling. Wide basins are adopted when paddy rice is in rotation with upland field crops. Since zero-level is the most adequate for paddy fields (Mao et al. 2004), it is interesting to have confirmed that zero-level is also the best option for higher performance of upland crops as defined in previous studies (Pereira et al. 2007).

An alternative way to appreciate the impacts of the spatial variability of microtopography on irrigation performance is to analyze the ratio R_Z (eq. 14) between Z_{adv} and Z_{tg} (Table 12). Results show that this ratio always increases when S_d increases, i.e., overirrigation increases with the basin surface unevenness. A value close to 1.0 indicates that a high DU_{lq} is achieved (cf. results in Fig. 6), also resulting in high potential application efficiency. If Z_{tg} would be larger, e.g. 100 mm, overirrigation would not occur for many cases with S_d = 2 cm and would be small with S_d = 3 cm. Ratios R_Z are smaller for the strip basins and larger for the narrow ones (Table 12). However, for the later the influence of the basin length is greater than that of the basin shape. Results for strip basins when $S_d \geq 3$ cm show that less overirrigation may be obtained for sloping fields and smaller inflow rates; for narrow and wide basins, better results for sloping basins refer to larger inflow rates. Differently, for precise leveled basins ($S_d \leq 2$ cm) the best results correspond to zero slope and large inflow discharges. These results justify the common option of farmers to apply large water depths (100 mm or more) and often adopting strip basins with lengths generally smaller than 100 m.

Basin type	Basin slope S_o (%)	Inflow rate (L s^{-1} m^{-1})	Z_{tg} = 80 mm					Z_{tg} = 100 mm				
			S_d (cm)					S_d (cm)				
			1	2	3	4	5	1	2	3	4	5
Strip basin	0.1	2	0.93	0.98	1.25	1.44	1.61	0.74	0.78	1.00	1.15	1.29
		4	0.93	1.04	1.34	1.53	1.64	0.75	0.83	1.07	1.22	1.31
	0	2	1.03	1.25	1.54	1.61	1.81	0.82	1.00	1.23	1.29	1.45
		4	1.10	1.24	1.39	1.58	1.74	0.88	0.99	1.11	1.26	1.39
Narrow basin	0.1	2	1.00	1.44	1.64	1.78	2.01	0.80	1.15	1.31	1.42	1.61
		4	1.04	1.21	1.42	1.69	1.93	0.83	0.97	1.13	1.35	1.55
	0	2	1.23	1.64	1.87	2.09	2.33	0.98	1.31	1.49	1.68	1.86
		4	1.25	1.40	1.62	1.92	2.15	1.00	1.12	1.29	1.53	1.72
Wide basin	0.1	2	0.81	1.18	1.38	1.65	1.88	0.65	0.94	1.11	1.32	1.50
		4	0.96	1.03	1.30	1.61	1.85	0.77	0.82	1.04	1.29	1.48
	0	2	1.04	1.33	1.58	1.85	2.03	0.84	1.06	1.26	1.48	1.62
		4	1.10	1.31	1.51	1.79	1.94	0.88	1.05	1.21	1.43	1.55

Table 12. Ratio between the infiltrated depth when the advance is completed, Z_{adv} (mm) and the target net depth (Z_{tg} = 80 and 100 mm) for various basin types, surface unevenness S_d (cm), basin slopes and inflow rates

5. Conclusion

Data on 116 basin irrigation fields, which cover a wide range of basin geometry and microtopography characteristics in various irrigation districts in North China were analyzed relative to the spatial variability of surface elevation differences (SED). The respective spatial structure is characterized with a spherical semivariogram model. Related data show that a medium or strong spatial dependence exist for the basins microtopography, and that a significant correlation exists between the semivariogram parameters and basin parameters (length, width, area, and the standard deviation S_d of SED).

Considering the characteristics of the spatial variability of SED, a procedure was developed for generating the spatial distribution of SED, and the number of SED generations required for each basin type and S_d was decided. field validation results showed that the stochastic tool developed for generating a spatial distribution of SED respecting a target mean and standard deviation is an useful research tool for a detailed analysis of to SED impacts on irrigation performance aimed at developing appropriate design criteria. These ones refer to land leveling, basin shape, basin lengths and inflow discharges.

Relative to leveling, if precision leveling is to be used, the standard deviation of surface elevation differences between the actual and the target design elevations should be $S_d < 2$ cm as already proposed in various studies. This threshold value should be used for both initial and maintenance land leveling. When this threshold is adopted both graded and zero leveled basins can be selected. Precise land leveling technology is available in China but due to the very intensive land use in North China, with wheat planted around five days after maize harvesting. and maize again following in the same land, very little time is left to perform precision leveling. Under these circumstances, it is acceptable to adopt graded basins as it is the general rule in China. When the slope is small such as analyzed herein (S_o = 0.1%) it results a distribution uniformity DU_{lq} smaller than for zero leveled basins but the excess infiltration relative to the target is smaller by about 20%. Thus, despite DU_{lq} is not maximized there are better chances for water saving. If uniformity is to be maximized, zero leveling is preferably adopted.

Following this study, it seems appropriate to adopt a decision support system and multicriteria analysis to better defining design options taking into consideration the costs and benefits associated with various possible alternatives, the expected impacts in water savings and the effects of uniformity of distribution on yields. These studies shall include different soils and infiltration characteristics as well as different basin sizes. A deeper understanding of economic, financial and environmental impacts is required to support developing appropriate design and issues for improving surface irrigation.

6. Acknowledgment

This research was supported by the National Natural Science Fund project No.50909100, the National High-Tech R&D Program Projects No. 2011AA100505. The collaborative Sino-Portuguese project on “Water Saving Irrigation: Technologies and Management” is also acknowledged. Thank Professor L.S. Pereira to give me good suggestions for this research work. Thanks are due to Zhang Shaohui and Li Fuxiang for contributing to the field experiments. The support by Dr. E. Playán on the use of the surface simulation model and further advising is sincerely acknowledged.

7. References

Barnes RJ (1991). The variogram sill and the sample variance. *Mathematical Geology* 23(4):673-678

Cai LG, Li YN, Liu Y, Qian YB (1998). Socio-economic aspects. Demonstration activities. In: Pereira, L.S. Liang, R.J., Musy, A. and Hann, M.(Eds.) *Water and Soil Management for Sustainable Agriculture in the North China Plain*. Dep. Engenharia Rural, Instituto Superior de Agronomia, Lisbon, pp. 382-405.

Clark I (1979) .Practical Geostatistics. Elsevier, London, 129 pp

Clemmens AJ, El-Haddad Z, Fangmeier DD, Osman HE-B (1999) .Statistical approach to incorporating the influence of land-grading precision on level-basin performance, *Trans. of ASAE*, 42(4): 1009-1017.

Clemmens AJ, Strelkoff TS, Playán E (2003). Field verification of two-dimensional surface irrigation model. *J Irrig Drain E-ASCE*, 129(6), 402-411

Deng HN (2002) .Method and Application of Probability Statistics. China Agriculture Press, Beijing (in Chinese).

Fabião MS, Gonçalves JM, Pereira LS, Campos AA, Liu Y, Li YN, Mao Z, Dong B (2003) .Water saving in the Yellow River Basin, China. 2. Assessing the potential for improving basin irrigation, Agricultural Engineering International Vol. V, LW 02 008. (http://www.cigrjournal.org/index.php/Ejounral/article/view/404).

Gonçalves JM, Pereira LS (2009). A decision support system for surface irrigation design. *J Irrig Drain E-ASCE*, 135(3): 343-356

Li YN, Calejo MJ (1998). Surface irrigation. In: Pereira LS, Liang RJ, Musy A, Hann M (eds) Water and Soil Management for Sustainable. *Agriculture in the North China Plain*. ISA, Lisbon, pp 236-303.

Li YN, Xu D, Li FX (2001). Modeling the influence of land leveling precision on basin irrigation performance. *Transactions of the CSAE*, 17(4):43-48 (in Chinese).

Li YN, Xu D, Li FX (2006). Development and performance measurement of water depth measuring device applied for surface irrigation. *Transaction of CSAE*, 22(1):32-36.

Liu Y, Cai JB, Li YN, Bai MJ (2003) .Assessment of crop irrigation requirements and improvements in surface irrigation in Bojili irrigation district. In: Pereira LS, Cai LG, Musy A, Minhas PS (eds), Water Savings in the Yellow River Basin. Issues and Decision Support Tools in Irrigation. China Agriculture Press, Beijing, pp 131-152.

Mao Z, Dong B, Pereira LS (2004) .Assessment and water saving issues for Ningxia paddies, upper Yellow River Basin. *Paddy and Water Environment* 2(2): 99-110.

Merriam JL, Keller J (1978) .Farm irrigation system evaluation: A guide for management. Agricultural and Irrigation Engineering Department, Utah State University, Logan, Utah, 271pp.

Mood AM, Graybill FA, Boes DC (1974) .Introduction to the theory of statistics. McGraw-Hill, New York, 564 pp.

Pannatier Y (1996) .VARIOWIN: Software for Spatial Data Analysis in 2D. Springer-Verlag, New York.

Pereira LS (1999). Higher performances through combined improvements in irrigation methods and scheduling: A discussion. *Agric. Water Manage.* 40 (2-3): 153-169.

Pereira LS, Gonçalves JM, Dong B, Mao Z, Fang SX (2007) .Assessing basin irrigation and scheduling strategies for saving irrigation water and controlling salinity in the Upper Yellow River Basin, China. *Agric. Water Manage.* 93(3): 109–122.

Pereira LS, Oweis T, Zairi A (2002). Irrigation management under water scarcity. *Agric. Water Manage*. 57: 175-206.

Playán E, Faci JM, Serreta A (1996a). Characterizing microtopographical effects on level-basin irrigation performance. *Agric. Water Manage*. 29:129-145.

Playán E, Faci JM, Serreta A (1996b). Modeling microtopography in basin irrigation. *J Irrig Drain E-ASCE*, 122(6): 339-347.

Playán E, Walker WR, Merkley GP (1994a). Two-dimensional simulation of basin irrigation: I: Theory. *J Irrig Drain Eng*, 120(5): 837-856.

Playán E, Walker WR, Merkley GP (1994b) .Two-dimensional simulation of basin irrigation: II: Applications. *J Irrig Drain Eng*, 120(5): 857-869.

Strelkoff TS (1990) .SRFR: A computer program for simulating flow in surface irrigation furrows-basins-borders. WCL Rep. 17, U.S. Water Conservation Laboratory, USDA/ARS, Phoenix.

Strelkoff TS, Clemmens AJ, Schmidt BV (2000) .ARS software for simulation and design of surface irrigation. In: Evans RG, Benham BL, Trooien TP (eds) Proceedings of the 4th Decennial National Irrigation Symposium, ASAE, St. Joseph, MI, pp. 290-297.

Walker WR (1998). SIRMOD – Surface Irrigation Modeling Software. Utah State University, Logan.

Walker WR, Skogerboe GV (1987). Surface Irrigation. Theory and Practice. Prentice-Hall, Englewood Cliffs, NJ.

Xu D, Li YN, Chen XJ, Xie CB, Liu QC, Huang B (2002). Study and Application of the Water Saving Irrigation Technology at Farm. China Agriculture Press, Beijing (in Chinese)

Xu D, Li YN, Li FX, Bai MJ (2005) .Analysis of feasible grid spacing in agricultural land levelling survey. *Transactions of the CSAE*, 21(2):51-55. (in Chinese)

Zapata N, Playán E (2000a) .Simulating elevation and infiltration in level-basin irrigation. J Irrig Drain Eng, 126(2): 78-84.

Zapata N, Playán E (2000b) .Elevation and infiltration in a level basin. I. Characterizing variability. *Irrigation Sci.*, 19: 155-164.

21

Performance of Smallholder Irrigation Schemes in the Vhembe District of South Africa

Wim Van Averbeke
Tshwane University of Technology
South Africa

1. Introduction

South Africa needs to raise employment and reduce poverty, particularly among rural African people. The New Growth Path released by the government in November 2010 was a response to the persistent unemployment problem. It aims to create five million new jobs by 2020. The New Growth Path intends to create 300 000 of these new jobs through the establishment of smallholder farmer schemes (Department of Economic Development, 2010). This suggests that policymakers believe that smallholder scheme development can create a substantial number of new employment opportunities in South Africa. However, the performance of the smallholder schemes that have been set up as part of the post-democratisation land reform programme has been dismal (Umhlaba, 2010). Assessments of smallholder irrigation schemes indicated that many of them also performed poorly (Bembridge, 2000; Machete et al., 2004; Tlou et al., 2006; Mnkeni et al., 2010). Yet, in water-stressed South Africa, expanding smallholder irrigation is one of the obvious options to trigger rural economic development. Elsewhere in the world, particularly in Asia, investment in irrigation was a key ingredient of the green revolution, which lifted large numbers of rural Asians out of poverty and created conditions that were conducive for the industrial and economic development that has occurred (Turral *et al*., 2010). A similar development trajectory has been recommended for South Africa and other parts of Sub-Saharan Africa (Lipton, 1996). So far, the developmental impact of smallholder irrigation in Sub-Saharan Africa has been limited (Inocencio *et al*., 2007).

In this chapter, associations between selected performance indicators and attributes of smallholder irrigation schemes in the Vhembe District of Limpopo Province, South Africa, are examined. For the purpose of this chapter, smallholder irrigation scheme was defined as an as an agricultural project that was constructed specifically for occupation by African farmers and that involved multiple holdings, which depended on a shared distribution system for access to irrigation water and in some cases also on a shared water storage or diversion facility. In 2011, there were 302 smallholder irrigation schemes in South Africa with a combined command area of 47 667 ha.

The objective of this chapter was to identify factors that had a significant effect on smallholder irrigation scheme performance. Knowledge of such factors could assist effective location and design of new schemes. Before focussing on the study itself, it was deemed important to provide a background to African smallholder agriculture in South Africa in general and smallholder irrigation scheme development in particular. This is done in the first part of this chapter. The study area and the materials and methods used to assess the population of smallholder irrigation schemes in the study area are presented in the second part. The results of the study are presented next. First, the characteristics of population of smallholder schemes in the study area are described. Next, the associations between a selection of smallholder scheme characteristics and four performance indicators are examined statistically. In the last part the results of the study are discussed and interpreted.

2. African smallholder agriculture and irrigation in South Africa: A brief history

2.1 African smallholder agriculture

In South Africa, traditional agriculture was disturbed in major ways by military and political subjugation of the different African tribes during the nineteenth century, followed by land dispossession, segregation and separation. These processes restricted the area where Africans held farm land to relatively small parts of the country, which combined covered about 13% of the total land area in 1994 (Vink & Kirsten, 2003). Over time, the territories in which Africans held land have been referred to as Native Areas, Bantu Areas, Bantustans and homelands but in this text the term homelands will be used to reflect the situation just prior to democratisation of South Africa in 1994. From when they were created in 1913, the homelands have been characterised by high rural population densities, small individual allotments of arable land and shared access to rangeland. The rangeland that was available to communities was inadequate to support sufficient livestock to meet even the most basic requirements of African homesteads in terms of draught power, milk, wool, meat and social needs (Lewis, 1984; Bundy, 1988; Mills & Wilson, 1952). African homesteads diversified their livelihoods in response to the lack of room to reproduce their land-based lifestyles. Until about 1970, migrant remittances, mostly from male members who worked in mines and cities, supported the reproduction of African rural homesteads (Beinart, 2001). From 1970 to 1990, income earned from employment inside the homelands became important (Leibbrandt & Sperber, 1997; Beinart, 2001). Homelands received substantial budget allocations from separatist South Africa to attend to local economic and social development. Employment was created in education, bureaucracy and business (Beinart, 2001). From 1990 onwards, rural homesteads increasingly depended of claiming against the state, in the form of old-age pensions and child support grants (Shah et al., 2002; Van Averbeke & Hebinck, 2007; Aliber & Hart, 2009; De Wet, 2011).

Despite the lack of room to farm, agricultural activities remained central in the livelihood strategy of a majority of rural homesteads until about 1950, even though the proportional and nominal contribution of agriculture to homestead income had been in decline for much longer (Houghton, 1955; Tomlinson Commission, 1955; Bundy, 1988). After 1950, rural African homesteads progressively withdrew from cultivating their arable allotments. For example, in Ciskei the cultivation of arable land dropped from an average of 82% in 1950 (Houghton, 1955) to 10% in 2006 (De Wet, 2010). Whilst the decline in cultivation has not necessarily been as dramatic in all homeland areas as it has been in Ciskei, the trend has been universal. As a result, for most African rural homesteads farming has become a livelihood activity that is of secondary importance. In 2006, of the 1.3 million African households with access to an arable allotment, only 8% listed agriculture as their main source of food. For less than one in ten households (9%) agriculture was a source of monetary income, with 3% referring to farming as their main source of income and 6% as an additional source of income. For the large majority, farming was merely an additional source of food (Aliber & Hart, 2009; Vink & Van Rooyen, 2009).

The deterioration of African farming received government attention from 1917 onwards (Beinart, 2003). Initial interventions were focused on the conservation of the natural resource base in the homelands. Land use planning, conservation of arable land using erosion control measures, rotational grazing using fenced grazing camps and livestock reduction schemes were some of the important measures taken by the state to check natural resource degradation (Beinart, 2003). More land was made available to reduce growing landlessness but these interventions had no positive impact on agricultural production. Overcrowding as the principal cause for the inability of African smallholders to produce enough to feed themselves, let alone make a living of the land, was pointed out by the Commission for the Socio-Economic Development of the Bantu Areas within the Union of South Africa (1955). This Commission was referred to as the Tomlinson Commission (1955) after Professor F.R. Tomlinson, who was its Chairperson. The Tomlinson Commission (1955) proposed the partial depopulation of the homelands to avail enough room for those who were to remain on the land to make a living from full-time farming. Expansion of irrigated farming, by upgrading existing irrigation schemes and establishing new schemes in the homelands, was one of the strategies proposed by the Tomlinson Commission (1955) to create new opportunities for African homesteads to make a full-time living from smallholder agriculture. The Tomlinson Commission (1955) had identified that smallholders on some of the existing irrigation schemes were making a decent living on irrigated plots of about 1.28 ha combined with access to enough grazing land to keep a herd of six cattle, which was the minimum number required for animal draught power. The master plan of the Tomlinson Commission (1955) to reduce the population in the homelands and establish economically viable farm units for African homesteads was never implemented. The proposal to expand smallholder irrigation did receive attention. It played an important role in irrigation scheme development in the Vhembe District, which will be discussed later.

2.2 African smallholder irrigation schemes

The use of irrigation by African farmers in South Africa appears to have two centres of origin. One of these centres was the Ciskei region of the Eastern Cape, where technology transfer from colonialists to the local people, resulted in the adoption of irrigated agriculture by African peasants (Bundy, 1988). These early smallholder irrigation developments were mostly private or mission station initiatives and involved river diversion. Most of these early African irrigation initiatives in the Eastern Cape did not last long (Houghton, 1955, Bundy, 1988). The other centre of origin was located in what is now the Vhembe District. Evidence of African irrigation in this area was provided by Stayt (1968), who conducted anthropological research among the Venda during the late nineteen-twenties and published the first account of his work in 1931. Box 1 cites Stayt's reference to African irrigation in Vhembe. This reference to early African irrigation in Vhembe contained in Box 1 is significant for two reasons, namely the apparent use of irrigated agriculture by local African people before exposure to European colonialists and their continued use, or at least re-adoption, of irrigated agriculture using stream diversion during the nineteen-thirties,. This suggests local interest, knowledge and affinity for the use of irrigation as a way of intensifying crop production.

> In the northwest of Vendaland there are traces of some very ancient occupation. Colonel Piet Moller, who was an early settler in the Zoutpansberg, has found what he considers indisputable evidence of ancient irrigation works. Most of the old furrows are near Chepisse and it appears that the water was diverted from a small stream there in a series of furrows to a distance of about four and a half miles south. Traces of furrows are also discernable at Sulphur Springs, and at several places by the Nzhelele river, where some of them have been reopened and are utilised by the BaVenda to-day. Colonel Moller says that when he first came across these some forty years ago (around 1880), there was no doubt about their antiquity; to-day they are very difficult to trace, as roads, modern agriculture, and furrows have altered the face of the country considerably and have particularly hidden the ancient workings.

Box 1. Reference to African irrigation in Vhembe (Stayt, 1968)

The Tomlinson Commission (1955) also identified the northern parts of South Africa as the area where smallholder irrigation schemes were functioning best, as is evident from its statement reproduced in Box 2.

> Among the various systems and types of settlement in the Bantu Areas, irrigation farming is undoubtedly the only form of undertaking in which, under European leadership and control, the Bantu have shown themselves capable of making a full-time living from farming, and of making advantageous use of the soil for food production.
>
> The interest shown by Bantu in irrigation farming varies from one locality to another. In some parts of the Transvaal (here reference is made to areas that are now part of Limpopo Province), the Bantu are so enthusiastic that they offer their labour free to construct canals to lead water from streams for the irrigation of their land, while in the Transkei and Ciskei (now part of the Eastern Cape), on the contrary, interest has waned to such a degree, that existing schemes have fallen into disuse.

Box 2. Reference to the performance of African smallholders on irrigation schemes during the period 1950-52 by the Tomlinson Commission (1955)

In 1952, when the Tomlinson Commission completed its data collection, it identified 122 smallholder irrigation schemes covering a total of 11 406 ha. This irrigated area was held by 7 538 plot holders, each holding a plot with an average size of 1.513 ha. All of these were river diversion schemes but it is not clear whether the water conveyance and distribution systems were lined or not. The Tomlinson Commission (1955) did distinguish between what appeared to be indigenous and state controlled irrigation projects, identifying state controlled schemes as performing considerably better than those controlled by African farmers themselves (Box 3).

The 'European control' mentioned in Box 3 referred to a set of institutional arrangements imposed by the state, which regulated allocation of water to farmers and land use, including choice of crops, and the provision of technical advice and marketing assistance for the crops that were prescribed to farmers. In line with this observation, the Tomlinson Commission (1955) recommended the construction of new smallholder irrigation schemes and the upgrading of existing schemes as a smallholder development strategy. The Tomlinson Commission (1955) identified a total area of 54 051 ha that had the potential for irrigation development in Bantu Areas and estimated that exploitation of this potential could enable the settlement of 36 000 farmer families, representing approximately 216 000 people. The Tomlinson Commission (1955) recommended that irrigation scheme development should occur in the form of simple canal schemes using river diversion by means of a weir and that uniform regulations should be applied to the running of these schemes. One of these regulations was that ownership and control over tribal land identified for irrigation scheme development needed to be transferred to the state before construction of the scheme. Another was that homesteads would be allocated plots that were 1.28 ha to 1.71 ha in size, as these were deemed adequate to provide for a livelihood based on full-time farming. A third was the enforcement of specified production systems on smallholder irrigation schemes. These production systems were to be designed, enforced and supported by state-appointed superintendents. Farmers who settled on these schemes held their plots under Trust tenure. This form of tenure provided the state with the necessary powers to prescribe land use and to expel and replace farmers whose practices did not comply with these prescriptions. In selected cases the state effectively used these powers to enforce the overall objectives of the schemes by evicting poorly performing families (Van Averbeke, 2008). This authoritarian and paternalistic approach by the state was not limited to irrigation schemes settled by Africans. The same approach had been used on state schemes established for settlement by white farmers during the Great Depression and WWII period (Backeberg and Groenewald, 1995).

> The Commission collected details of the production achieved on the controlled Olifants River irrigation scheme and the uncontrolled Njelele River scheme (Vhembe District). The average size holding were 1.53 morgen (1.3 ha) and 1.71 morgen (1.5 ha), respectively, and other physical factors were approximately equal. It was found that the average income per settler on the Olifants scheme was £110.69 as compared with £28.79 on the Njelele scheme. The average yield of grain of all sorts was 47.07 bags (4270 kg) (fil in) per settler on the Olifants, as against 9.2 bags (835 kg) on the Njelele scheme. This is a clear indication that irrigation schemes for Bantu are successful when under efficient control and guidance and that the average Bantu family on 1.5 morgen (1.28 ha) under such schemes, can make a gross income of £110.7 per annum, which renders it unnecessary for members of the family to seek employment elsewhere to supplement the family income.

Box 3. Comparison of the performance of African smallholders on indigenous irrigation schemes with those on irrigation schemes under state control (Tomlinson Commission, 1955)

Construction of smallholder canal schemes in South Africa was continued until the nineteen-seventies. The 2011 update of the smallholder irrigation scheme data base created by Denison and Manona (2007) indicated that there were 74 smallholder canal schemes left in South Africa. Sixty-seven of these were operational, six were not operational and of one scheme the operational status was not known. The combined command area of existing gravity-fed canal schemes was 11 966.2 ha, which represented 25.1% of the total smallholder irrigation scheme command area in South Africa. Surface irrigation was also practised on 20 schemes that used pumping, sometimes in combination with gravity. Among these 20 schemes, 14 of were operational and six were not. Combined they had a command area of 4 113.7 ha, 8.6% of the total.

From the nineteen-seventies onwards, the design of smallholder irrigation schemes in South Africa was influenced by the modernisation paradigm. This paradigm was based on the belief that modern, capital-intensive infrastructure, to be paid for by the intensive production of high-value crops, could lift smallholders out of poverty (Faurès *et al.*, 2007). Pumping and overhead irrigation became the norm in smallholder irrigation scheme development in South Africa. In 2011, there were 175 smallholder irrigation schemes that used overhead irrigation. Combined they had a command area of 27 757.6 ha, 58.2% of the total. Among these 175 schemes, 111 were operational, 59 were not and of five the operational status was not known. Pumped overhead schemes covered a total command area of 16 497.1 ha, gravity-fed overhead schemes 4 451 ha and schemes where gravity and pumping occurred in combination had a total command area of 6 903.5 ha.

Distinctive of the modernisation paradigm in smallholder irrigation scheme development was the establishment of large projects. In many of the large smallholder schemes that were constructed in South Africa, the design was characterised by functional diversification and centralisation of scheme management. Typically, these large schemes were designed to perform three functions, namely a commercial function, a commercial smallholder development function and a subsistence function. The commercial function was performed by allocating a substantial part of the scheme area to a central unit that was farmed as an estate. Farming on this estate used management and labour (Van Averbeke *et al.*, 1998). The commercial smallholder development function was implemented by allocating a limited number of 'mini-farms' to selected African homesteads, who were judged to have the aptitude to make a success of small-scale commercial agriculture. These mini-farms ranged between 5 ha and 12 ha in size. (Van Averbeke *et al.*, 1998), The subsistence function was put into practice by providing large numbers of African homesteads with access to food plots, ranging from 0.1 ha to 0.3 ha in size (Van Averbeke *et al.*, 1998). In some instances complex arrangements had to be made to implement this multi-functional design, because land holders had to be compensated for handing over their dryland allotments to create room for the central unit estate. A good example was the 2 830 ha Ncora Irrigation Scheme, established in 1976 in the Transkei region of the Eastern Cape. In return for availing their allotments to the scheme, the 1 200 existing land holders at Ncora were offered the right to 0.9 ha of irrigation land. They were given the choice of farming the entire allocation themselves or handing over two-thirds of their allotment to the central unit and remain with a 0.3 ha plot for own use. The latter option provided land holders with production inputs free of charge and an annual dividend derived from the profits made by the central unit. Management of these large schemes was centralised and in the hands of specialised parastatals established by homeland governments (Van Rooyen & Nene, 1996; Van Averbeke et al., 1998; Lahiff, 2000). The financial viability of this type of smallholder schemes was dependent on the performance of the central unit. Records show that the financial performance of these central units never met the predictions (Van Averbeke *et al.*, 1998). State subsidies were persistently required to keep these schemes afloat. Taking an extreme example, in 1995, the central unit of Ncora Irrigation Scheme required a budget of R21.3 million. It had 650 employees at a cost R16.6 million and operational costs amounting to R4.8 million. The income of the central unit in 1995 was R2.8 million, way short of even meeting its operational costs.

Following the democratisation of South Africa in 1994, the provincial governments decided to dismantle the agricultural homeland parastatals and transfer the management of smallholder irrigation schemes to the farmer communities who benefitted from them. Elsewhere in the world, a similar process, referred to as 'Irrigation Management Transfer' (IMT) had been occurring. Reducing public expenditure on irrigation, improving productivity of irrigation and stabilising of deteriorating irrigation systems were the three main reasons why IMT was implemented by governments (Vermillion, 1997). In South Africa, the dismantling of homeland parastatals and IMT proceeded very swiftly. It started in 1996 in the Eastern Cape and ended in 1998 in Limpopo Province. IMT affected all projects where parastatals were offering services to smallholders. Its effects were most strongly felt on the large, modern smallholder irrigation schemes, because these projects were the most complex to manage. Having been centrally managed from inception, levels of dependency on external management among farmers on these schemes were exceptionally high (Van Averbeke et al., 1998). Farming collapsed as soon as IMT had been implemented on these schemes (Bembridge, 2000; Laker, 2004). Small irrigation schemes, particularly the canal schemes, were more resilient and continued to operate, albeit at reduced levels (Kamara et al., 2001; Machete et al., 2004).

Besides IMT, the nineteen-nineties also saw the establishment of several new smallholder irrigation schemes. Conceptually, these new schemes were aligned with the Reconstruction and Development Programme (RDP). This Programme was the national development framework that applied at that time. It was aimed at eradicating poverty and improving the quality of life among poor African people in rural areas and informal urban settlements. Irrigation development focused on improving food security at community or group level and favoured the establishment of small schemes. In 2006, Denison and Manona (2007) identified 62 smallholder irrigation schemes that were established during this era, but combined they only covered 2 383 ha, clearly indicating their limited size (38.4 ha on average). Typically, these projects used mechanical pump and sprinkler technology to extract and apply irrigation water.

When GEAR (Growth, Employment and Redistribution) superseded the RDP as the overall development policy of South Africa, the strategy to eradicate poverty shifted from funding community-based projects to pursuing economic growth through private sector development. Existing irrigation schemes were identified as important resources for the economic development of the rural areas, but they required revitalisation first. The Revitalisation of Smallholder Irrigation Schemes (RESIS) of the Limpopo Province stood out for its comprehensiveness. The RESIS programme evolved from the WaterCare programme, which was launched in 1998 and ran for five years (Denison and Manona, 2007). The WaterCare programme was aimed at revitalizing selected smallholder irrigation schemes in the Province, not only infrastructurally, but also in terms of leadership, management and productivity. Using a participatory approach, WaterCare involved smallholder communities in planning and decision making and provided training to enable these communities to take full management responsibility over their schemes (Denison & Manona, 2007). In February 2000, Mozambique and the Limpopo Province were ravaged by cyclone Conny (Christie & Hanlon, 2001). Heavy rains caused widespread floods and damage to roads, bridges and also to the weirs that provided water to many of the smallholder canal schemes (Khandlhela & May, 2006). Declared a disaster area, the Limpopo Province was allocated special funding to repair the damage to its infrastructure, providing impetus to the WaterCare programme. In 2002, the Limpopo Province broadened the scope of its irrigation scheme rehabilitation intervention by launching a comprehensive revitalisation programme, called RESIS (REvitalisation of Smallholder Irrigation Schemes). RESIS adopted the participatory approach of the WaterCare programme, but planned to revitalise all smallholder schemes in the Province (Denison & Manona, 2007). As was the case in the WaterCare programme, RESIS combined the reconstruction of smallholder irrigation infrastructure with the provision of support to enable effective IMT. In support of IMT, the programme dedicated one-third of the revitalisation budget to capacity building among farmers. Guidelines for the sustainable revitalisation of smallholder irrigation schemes, which covered the building of capacity among irrigator communities were developed by De Lange et al.(2000). RESIS also sought to enhance commercialisation of the smallholder farming systems on the schemes, in order to improve the livelihood of plot holder homesteads (Van Averbeke, 2008).

During the WaterCare programme and the first phase of RESIS (1998-2005), the emphasis was primarily on the rehabilitation of the existing scheme infrastructure and on sustainable IMT, and less on commercialisation. Canal schemes that were revitalised during this phase remained canal schemes. However, in 2005, commercialisation became the principal development objective of RESIS. The shift in emphasis was probably influenced by the Black Economic Empowerment (BEE) strategy that was introduced in South Africa, first in the mining sector and later on also in other sectors of the economy, including agriculture (Van Averbeke, 2008). Nationally, the BEE strategy was aimed at increasing the share of black people in the economy and it emphasized entrepreneurship. In 2005, the Limpopo Department of Agriculture launched the second phase of RESIS, named RESIS-RECHARGE. The Department equated canal irrigation with subsistence farming and inefficient water use. Consequently, it discouraged and later on rejected revitalisation of canal infrastructure. Instead it funded the transformation of canal schemes into schemes that used modern irrigation technology, such as micro-irrigation, centre pivot and floppy sprinkler systems. Implementation of these new irrigation systems obliterated existing plot boundaries. To get production on these revitalised modern schemes on a commercial footing, the Department engaged the services of a strategic partner in the form of a commercial farmer, who was tasked with running the entire operation. Plot holders were compensated for availing their land holdings by means of dividends, which amounted to half of the net operating income. They no longer had an active part in farming. In the Vhembe District, two smallholder irrigation schemes were revitalised in this way, namely Makuleke and Block 1A of the Tshiombo scheme. The others remained unaffected. With reference to the use of micro-irrigation on smallholder irrigation schemes in South Africa, in 2011 there were 20 such schemes, 11 operational and nine non-operational. Combined they had a command area of 3 830 ha, 8.0% of the total.

3. Performance of smallholder irrigation schemes in South Africa

Globally, assessment of the performance of irrigated agriculture has received considerable attention, not in the least because of growing competition for water from other sectors (Faurès et al., 2007). Molden et al. (1998) developed a set of nine indicators to enable comparison of irrigation performance across irrigation systems. These covered irrigated agricultural output, water supply and financial returns. However, for smallholder irrigation schemes in South Africa the data required to calculate the nine indicators are rarely available. Most investigations into the performance of South African smallholder irrigation schemes used operational status, condition of the irrigation system, observations of cropping intensity and farm income in selected instances for assessment purposes. Generally, the conclusion of these studies has been that the contribution of smallholder irrigation schemes to social and economic development of irrigation communities has been far below expectations. (Bembridge & Sebotja, 1992; Bembridge, 1997; Bembridge, 2000; Machete et al., 2004; Tlou et al., 2006; Fanadzo et al., 2010). However, against a background of poor performance of smallholder irrigation schemes, few if any of the studies attempted to identify factors that appeared to contribute to differences in performance among these schemes. Such information could assist effective location and design of new schemes and also suggest priorities when planning the revitalisation of existing schemes.

4. Materials and methods

The Vhembe District is located in the Limpopo Province of South Africa (Fig.1), and is the most northern district of the Limpopo Province (Fig.2).

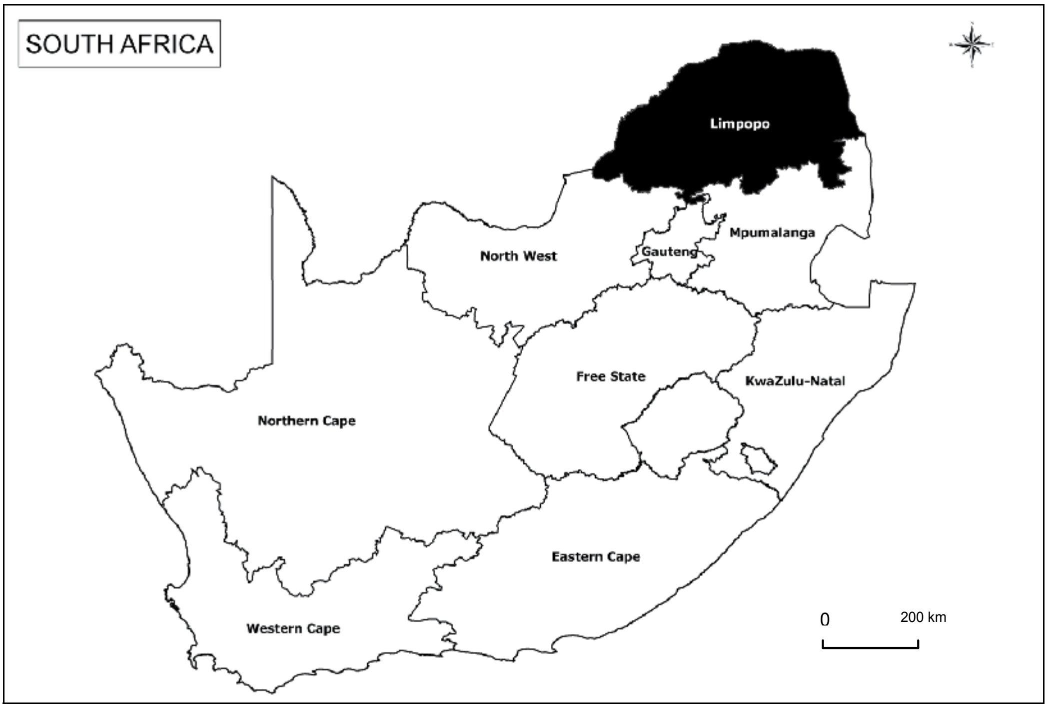


Fig. 1. The Limpopo Province in the north of South Africa

Vhembe borders Zimbabwe in the north and Mozambique in the east. It incorporates the territories of two former homelands, namely Venda and Gazankulu. The Venda homeland was created for the Venda-speaking people. Gazankulu was the territory allocated to the Tsonga-speaking people, also known as the Shangaan. Culturally, the BaVenda are closely associated with the Shona people of Zimbabwe, whilst the cultural roots of the Shangaan are in Mozambique.

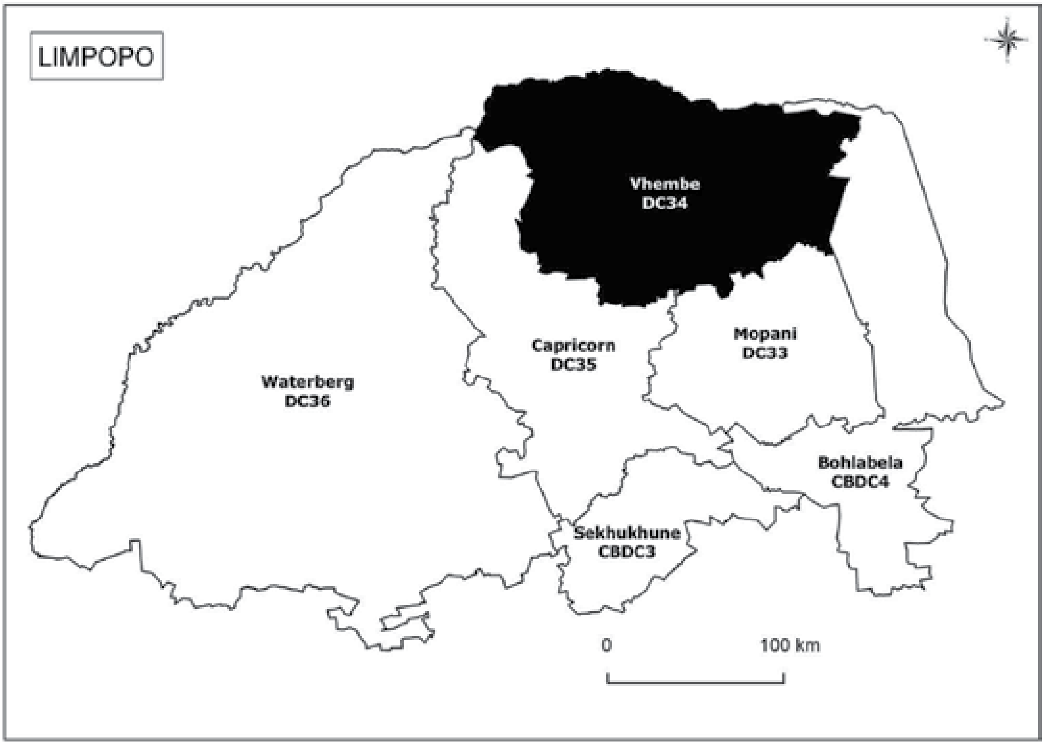


Fig. 2. Location of the Vhembe District in the Limpopo Province

Smallholder irrigation schemes in the Vhembe District were studied by means of a census. The census covered all smallholder irrigation schemes contained in the Vhembe register of the Limpopo Department of Agriculture, which was used as the sampling frame. A structured interview schedule was compiled for use as the survey instrument. The survey was conducted over a period of 10 months and involved four visits to the study area, each lasting between five and ten days. Work started in November 2008 and the last schemes on the list were visited during August 2009. Subsequently, the field data were scrutinised to identify data that were missing or needed verification. All the data queries that were identified were resolved during a follow-up visit to the study area in November 2009. Care was taken to achieve the greatest possible degree of reliability. Where possible, a small panel consisting of farmers, preferably members of the scheme management, and the extension officer were interviewed. At a few schemes only the extension officer or only farmers participated in the interview. Following the completion of the interview, a transect walk of the scheme was done and pictures were taken of selected features. A total of 42 schemes were identified but data collection at the Tshiombo Irrigation Scheme was done for each of the seven sub-units because of important differences amongst them. All other schemes were not subdivided, even when they consisted of multiple hydraulic units, referred to as irrigation blocks.

The first level of analysis was aimed at describing the population of smallholder irrigation schemes in the study area. For this analysis, the population was described one variable at a time, using descriptive statistics to generate summaries. The results provided a useful indication of the issues that affected smallholder irrigation in the study area and the diversity that surrounded these issues. The second level of analysis involved the testing of associations between four variables that were selected as performance indicators and a selection of independent variables that described the schemes.

The four performance indicators were operational status, number of years the scheme had been in operation, cropping intensity and degree of commercialisation. Operational status was selected because it is the primary indicator of performance. Once a scheme has stopped to operate, land use reverts to dryland agriculture. The number of years a scheme had been in operation was selected as an indicator of the durability of the system, which, in turn affects the rate of return on investment. Cropping intensity is a widely used indicator of the intensity with which water and land is being used in irrigated agriculture (Molden et al. 2007). Degree of commercialisation was selected because commercialisation has been shown to increase production and accelerate linkages in smallholder agriculture (Makhura et al., 1998).

The scheme characteristics that were considered in the analysis are shown in Table 1.

Scheme characteristic	**Ranking criteria**	**Performance indicator**			
		Operational status (n=48)	No of years in operation (n=48)	Cropping intensity (n=35)	Degree of commercialisation (n=35)
Hydraulic head	1 = gravity; 2 = pumped	Yes	Yes	Yes	Yes
Irrigation method	1 = surface; 2 = overhead; 3 = micro	Yes	Yes	Yes	Yes
Scheme area	Command area (ha)	Yes	Yes	No	No
No of plot holders	Population count	No	Yes	No	No
Plot size	Plot size (ha)	No	Yes	Yes	Yes
Organisation of production	1= individual; 2 = group	No	Yes	No	No
Water restrictions at scheme level	1 = no restrictions; 2 = seasonal restrictions; 3 = perpetual restrictions	No	No	Yes	No
Cash based land exchanges	0 = not practised; 1 = practised	No	No	Yes	Yes
Water theft	0 = not practised; 1 = practised	No	No	Yes	No
Effectiveness of scheme fence	1= effective; 2 = partially effective; 3 = not effective	No	No	Yes	No
Distance to urban centre	Distance by road (km)	No	No	Yes	Yes

Table 1. Selected characteristics of smallholder irrigation schemes in Vhembe, their ranking and the association of the performance indicators they were tested for

Inclusion of the scheme characteristics shown in Table 1 was justified as follows: hydraulic head for its direct effect on operational costs; irrigation method as an indicator of modernisation; scheme area and number of plot holders as indicators of management complexity; plot size for its association with degree of commercialisation identified in other studies (Van Averbeke et al., 1998; Bembridge, 2000; Machete et al., 2004); organisation of production, because group-based land reform projects have been shown to be prone to failure (Umhlaba, 2009); water restrictions because water is a production factor (Perry & Narayanamurthy, 1998); cash based land exchanges as an indicator of social and institutional responsiveness to demand for land (Shah et al., 2002); water theft as an indicator of social order (Letsoalo & van Averbeke, 2006); effectiveness of the scheme fence as a recurrent constraint in smallholder agriculture; and distance to urban centre as a measure of access to sizeable produce markets. Associations between scheme performance and scheme characteristics were assessed using Spearman's rank correlation. Scheme characteristics, their ranking and the association of the performance indicators they were tested for, are shown in Table 1. All 48 schemes were included in the analysis of operational status and number of years the scheme had been in operation. Schemes that were not operational (11), as well as two schemes that were no longer managed by plot holders following their revitalisation were excluded from the analysis of cropping intensity and degree of commercialisation.

5. Results

5.1 Summary description of smallholder irrigation schemes in Vhembe

Selected characteristics of the smallholder irrigation schemes in Vhembe District are presented in Table 2. Keeping in mind that the seven hydraulic units of Tshiombo were treated as separate schemes, 37 (77%) of the 48 smallholder schemes were operational and 11 were not. The smallest among the 48 schemes, Klein Tshipise, had a command area of only 8.5 ha, whilst the largest, Tshiombo, had a command area of 847 ha when its seven sub-units were combined. Together, the 48 schemes covered a total command area of 3760.1 ha, of which 3012.4 ha (80%) was located on schemes that were operational. The actual irrigated area on the schemes that were operational was 2693.1 ha. Two reasons were identified for the difference of 319.3 ha between command area and actual irrigated area on operational schemes. The first was infrastructural malfunctioning, which resulted in parts of the command area being withdrawn from irrigation. Schemes affected and areas involved were Khumbe (59 ha), Dopeni (17 ha) and Xigalo (30 ha). The second was that during revitalisation, parts of the command area were excluded, as in the case of Tshiombo Block 1A (8 ha) and Makuleke (204 ha).

At Tshiombo Block 1A (Fig.3), which was converted from canal to floppy irrigation, various small parts of the command area were not used because they did not fit the layout of the new irrigation system. At Makuleke, centre pivots limited use of the command area to selected parts of the scheme that were sufficiently large and homogeneous to accommodate a centre pivot. The food plot section of the scheme was never revitalised and remained non-operational at the time of the survey. Palmaryville lost 1.3 ha, when the demonstration plot was privatised.

5.2 Irrigation scheme development in Vhembe

The post-WWII period up to 1969 was very important for smallholder irrigation scheme development in Vhembe. Seven schemes with a total command area of 659.6 ha were

Scheme name	Operational	Number of years operational	Command area (ha)	Number of plot holders	Average plot size (ha)	Hydraulic head	Irrigation method
Nesengani	Yes	42	13.7	28	0.415	Pumped	Surface
Nesengani B1	No	17	20.6	116	0.178	Pumped	Overhead
Nesengani B2	No	17	40.9	116	0.352	Pumped	Overhead
Nesengani C	No	17	31.2	131	0.238	Pumped	Overhead
Dzindi	Yes	56	136.2	102	1.285	Gravity	Surface
Khumbe	Yes	56	145.0	138	0.623	Gravity	Surface
Dzwerani	No	20	124.0	248	0.500	Pumped	Overhead
Palmaryville	Yes	59	92.0	70	1.296	Gravity	Surface
Lwamondo	No	6	15.0	75	0.200	Pumped	Micro
Mauluma	Yes	45	38.0	30	1.267	Gravity	Surface
Mavhunga	Yes	45	47.5	32	1.532	Gravity	Surface
Raliphaswa	Yes	46	15.0	13	1.154	Gravity	Surface
Mandiwana	Yes	46	67.0	40	1.675	Gravity	Surface
Mamuhohi	Yes	46	77.0	61	1.262	Gravity	Surface
Mphaila	Yes	21	70.6	59	1.197	Pumped	Overhead
Luvhada	Yes	58	28.8	79	0.365	Gravity	Surface
Rabali	Yes	59	87.0	68	1.279	Gravity	Surface
Mphepu	Yes	49	132.8	133	0.998	Gravity	Surface
Tshiombo 1	Yes	48	60.5	47	1.287	Gravity	Surface
Tshiombo 1a	Yes	1	128.6	100	1.286	Pumped	Overhead
Tshiombo 1b	Yes	45	122.0	115	1.061	Gravity	Surface
Tshiombo 2	Yes	46	126.0	98	1.286	Gravity	Surface
Tshiombo 2a	Yes	48	173.5	114	1.522	Gravity	Surface
Tshiombo 3	Yes	45	128.4	100	1.286	Gravity	Surface
Tshiombo 4	Yes	46	56.0	112	0.500	Gravity	Surface
Lambani	No	4	260.0	16	16.250	Pumped	Surface
Phaswana	No	8	16.7	16	1.044	Pumped	Surface
Cordon A	Yes	45	43.7	38	1.150	Gravity	Surface
Cordon B	Yes	45	82.3	65	1.266	Gravity	Surface
Phadzima	Yes	45	102.3	103	0.993	Gravity	Surface
Makuleke	Yes	2	37.3	29	1.286	Pumped	Overhead
Rambuda	Yes	58	170.0	132	1.288	Gravity	Surface
Murara	Yes	42	70.0	7	10.000	Gravity	Surface
Dopeni	Yes	46	30.0	6	5.000	Gravity	Surface
Makhonde	No	10	83.0	58	1.431	Pumped	Micro
Sanari	No	17	17.0	11	1.870	Pumped	Micro
Tshikonelo	No	14	10.0	15	0.670	Pumped	Overhead
Chivirikani	Yes	28	68.3	112	0.609	Pumped	Overhead
Gonani	Yes	13	8.5	30	0.295	Pumped	Overhead
Folovhodwe	Yes	54	70.0	24	2.197	Gravity	Surface
Klein Tshipise	Yes	36	60.0	60	1.000	Gravity	Surface
Morgan	Yes	40	56.7	35	1.620	Gravity	Surface
Makumeke	Yes	5	17.0	63	0.269	Pumped	Micro
Dovheni	Yes	11	60.0	14	2.143	Pumped	Overhead
Mangondi	No	15	48.0	38	1.260	Pumped	Micro
Xigalo	Yes	5	22.0	24	1.080	Pumped	Micro
Garside	Yes	45	13.7	28	0.415	Gravity	Surface
Malavuwe	Yes	19	20.6	116	0.178	Pumped	Overhead

Table 2. Selected characteristics of the population of smallholder irrigation schemes in Vhembe District

Fig. 3. Revitalisation of Tshiombo Block 1A replaced the secondary canals and concrete furrows that conveyed water to the edge of individual farmers' fields with a centrally operated floppy sprinkler system that covers the entire hydraulic unit

established between 1951 and 1959. An additional 21 schemes with a total command area of 1978 ha were constructed during the decade that followed. This means that 2637.6 ha (70% of the existing smallholder irrigation scheme command area in Vhembe) were established between 1951 and 1969. All of the schemes that were constructed during this period were canal schemes. Nesengani, established in 1968, was the only canal scheme that made use of a pump to extract water to small concrete reservoirs from where it was gravitated to the plots. All other canal schemes extracted water by means of a weir or by means of spring diversion and relied entirely on gravity to convey water to the plots. All but one of the schemes that were constructed as canal schemes remained operational as canal scheme in 2009 but several had been fully or partially refurbished. The only exception was Block 1A of Tshiombo, which was recently (2008-09) transformed into a floppy irrigation scheme.

The period 1970 to 1979, which saw the construction of the last two canal schemes in Vhembe, namely Morgan and Klein Tshipise (Fig.4) in 1974, was a quiet period for smallholder irrigation development. Renewed activity occurred from 1980 onwards and was associated with the commencement of homeland self-government (Beinart 2001). All smallholder irrigation schemes that were established from 1980 onwards used pumps and pressurised irrigation systems. Dzwerani, established in 1980, was the first pressurised smallholder irrigation scheme in Vhembe. Non-operational at present, the 128 ha scheme at Dzwerani involved the pumping of water from the Dzondo River close to the confluence with the Dzindi River and the application of water by means of dragline sprinklers. Dzwerani was unique in that the 0.5 ha irrigation plots were also used for residential purposes. The idea for this development followed a visit by President Mphephu of the Venda homeland to Israel, where he observed similar arrangements. Dzwerani became a presidential pet project that received full financial support towards the cost of pumping and also towards other inputs, resulting in the development of a high degree of dependency on the state among the plot holder community. The project stopped operating when the pump was washed away during the 2000 flood. During the period 1980 to 1989, 10 of the existing schemes came into being with a combined command area of 495.8 ha. An additional 8 schemes were created between 1990 and 1999, with a combined command area of 506.7 ha. Most of these schemes were developed before 1998, when the homeland agricultural parastatals were still operational.

Fig. 4. The 8.5 ha Klein Tshipise scheme sourced its water from a spring and was the last canal scheme to be constructed in Vhembe, which occurred in 1974

During the first decade of the 21st century, the emphasis of state intervention was on revitalisation of existing schemes rather than on the creation of new schemes. Only two new schemes were established during this period, covering a modest command area of 120 ha. By the end of 2009, 10 of the 48 schemes covering a command area of 902.3 ha (24.0%) had been completely revitalised. Another 12 schemes covering a command area of 1083.3 ha (28.8%) had been partly revitalised and an additional two schemes with a combined command area of 61.5 ha (1.6%) were being revitalised. This brought the total number of schemes that had benefited from revitalisation, or would so soon, to 24, which was exactly half of the total. Combined the schemes that benefitted from revitalisation support covered 54.4% of the total smallholder scheme command area of 3760.1 ha, which left 1713 ha (45.6%) untouched.

5.3 Plot holder populations and plot sizes

Smallholder scheme land in Vhembe was held by a total of 3250 plot holders. Makhonde, with 7 plot holders was the scheme with the smallest plot holder population, whilst Tshiombo, when its seven sub-units were combined, had the largest with 660 plot holders. Dividing the total command area of the smallholder schemes by the total number of plot holders showed that on average, a Vhembe plot holder held 1.1570 ha of land, of which 0.8286 was operational irrigation land. However, plot size varied among the schemes. The smallest average plot size (0.178 ha) was found at Nesengani B1. Phaswana had the largest average plot size. The most common average plot size ranged between 1.01 ha and 1.5 ha and was found on 22 schemes. Plots in this size range were also dominant among the population of plot holders. A total of 1431 plot holders (44%) held plots that fitted in this size class.

5.4 Water sources, extraction and adequacy

Extraction of water directly from rivers using pumps or by means of weir diversion were the two most common ways in which smallholder schemes sourced their irrigation water. Spring water was used at two of the smaller schemes, namely Klein Tshipise (8.5 ha) and Luvhada (28.8 ha) and at Garside, spring water was used as a supplementary source. Makuleke was the only scheme that obtained its water from a dam. Surface irrigation, which invariably involved the use of short furrow irrigation (Fig.5), was dominant and occurred on 28 of the 48 schemes. All other methods of applying water were of secondary importance, perhaps with the exception of micro-irrigation (micro jet and drip), which was found on eight schemes but only two of these were operational in 2009.

Fig. 5. Short furrow irrigation at the Dzindi canal scheme

Generally, irrigation water availability was reasonably adequate, because only 5 of the 48 schemes reported year-round limitations, whilst on 21 schemes availability was said to be unlimited. Seasonal limitations in availability were mostly encountered on canal schemes. Four of the five schemes that reported availability to be always limited consisted of the last four irrigation blocks of Tshiombo, where lack of water was caused, at least in part, by the front-end blocks extracting more than their share, leaving too little for the tail-end blocks. Front-end tail-end differences in access to water among farmers were commonly reported on canal schemes. Mangondi, a drip irrigation scheme that was not operational in 2009, was the other scheme where water was always limited. Here the problem appeared not to be the source (Levhubu River) but rather the way the extraction system had been set up. Farmers used various ways of dealing with lack of irrigation water. In order of frequency of occurrence these included reducing the area planted to crops (53%), exchanging water among themselves (49%), stealing water from others (44%), reducing the frequency of irrigation (42%), irrigating at night (33%), planting crops that required less water (27%) and extracting water privately from the source using portable pumps (7%).

Only 27 schemes had a water license issued by the Depart of Water Affairs. Payment for water occurred at 17 schemes but water was paid for by the Limpopo Department of Agriculture, not the farmers. Water user associations had been established on 28 schemes, but with few exceptions these were not functional. Participation of scheme communities in catchment management activities was limited to a single case. On all but five schemes, management of water extraction and distribution was in the hands of an elected plot holder committee. At Tshiombo Block 1A and Makuleke, the commercial partner was in control and at Sanari (micro irrigation) and Dovheni (designed as a sprinkler line scheme), there was no management organisation and farmers were allowed to draw water whenever they wanted. At Phaswana, water management was the responsibility of the farmer cooperative, but the scheme was no longer operational.

Formal water management rules (captured in writing) had been drawn up at 37 schemes. At one scheme rules existed but had not been written up. The remaining schemes had no rule system in place to manage water. These included Lwamondo (collapsed micro irrigation scheme), Phaswana (non-operational micro irrigation scheme), Tshiombo Block 1A and Makuleke (revitalised schemes that had a commercial partner, who operated the scheme) and the pressurised schemes of Gonani and Dovheni, where water availability was said not to be limiting.

5.5 Land tenure and exchange

The Trust tenure system was by far the most prevalent tenure system on smallholder irrigation schemes in Vhembe. The implication was that land identified for the development of irrigation schemes had been detribalised and transferred to the state before the scheme was constructed. Trust tenure is regarded as the least secure of all systems that applied to African land holding and has been identified as a possible reason for the lack of land exchanges on smallholder irrigation schemes (Van Averbeke, 2008). Schemes with traditional tenure were usually established quite recently but there was one exception. Luvhada, a project developed in 1952 by the community of Mphaila without state assistance also had traditional tenure. Despite the prevailing Trust system of tenure, land exchanges occurred on 72% of the schemes, which was more common than expected. On schemes where land exchanges occurred the basis for the exchange in order of importance was cash (82%), free land preparation of own parcel (52%), a share of the crop (27%) and just as a favour (9%). The maximum duration of land exchange arrangements on schemes where such arrangements occurred was more than two years in 67% of the cases, up to two years in 12% of the cases and limited to a single season in 21% of the cases.

5.6 Farming systems, cropping intensity and degree of commercialisation

The most common farming system involved the production of grain (mostly maize) and vegetables. This farming system was found on 73% of the schemes. The crops that were incorporated in this farming system served both as food crops for own consumption and as crops than could be sold locally (Fig.6).

Fig. 6. The main farming system on smallholder irrigation schemes involved the production of maize and vegetables, both of which could be used for own consumption or sales

All other farming systems (primarily tropical fruit) were less important. In most cases they were established through the intervention of a homeland parastatal or through the implementation of the Joint Venture model. This model transferred control of the scheme to a commercial partner. In return for the release of their land for use by the Joint Venture, plot holders received dividends, which amounted to half of the net operating income. Cropping intensity varied considerably among the schemes. The majority of schemes had cropping intensities that ranged between 0.8 and 1.6. Schemes with cropping intensities higher than 1.2 were considered to be really active. The highest cropping intensity of 2.0 was found at Tshiombo Block 1A and Makuleke. Both were Joint Venture schemes where the commercial partner did all the farming. Across operational schemes, the proportion of produce that was sold was 50.6%, which was about 5% higher than the 45% recorded in the 1952 survey of smallholder irrigation schemes by the Tomlinson Commission (1955). The difference was partially due to the exceptionally high proportion of produce sold (99%) at the Makuleke and Tshiombo Block 1A Joint Venture schemes.

6. Performance assessment

The results of the statistical analysis of the association of the four performance indicators and selected characteristics of smallholder irrigation schemes in Vhembe are summarised in Table 3. All 48 schemes were included in the analysis of operational status and durability (number of years in operation). For the analysis of cropping intensity and degree of commercialisation, all non-operating schemes and the two schemes where a strategic partner was doing all the farming were excluded from the analysis.

Scheme characteristic	Performance indicator			
	Operational status (n=48)	**No of years in operation** (n=48)	**Cropping intensity** (n=35)	**Degree of commercialisation** (n=35)
Hydraulic head	-0.618 (0.000)	-0.848 (0.000)	0.057 (0.187)	0.270 (0.029)
Irrigation method	-0.707 (0.000)	-0.847 (0.000)	0.189 (0.071)	0.373 (0.007)
Scheme area	0.154 (0.074)	0.394 (0.002)	-	-
No of plot holders	-	0.348 (0.004)	-	-
Plot size	-	0.019 (0.225)	0.104 (0.104)	0.212 (0.055)
Organisation of production	-	-0.266 (0.018)	-	-
Water restrictions at scheme level	-	-	-0.438 (0.002)	-0.031 (0.215)
Cash based land exchanges	-	-	-0.014 (0.235)	-0.019 (0.229)
Water theft	-	-	-0.244 (0.041)	-
Effectiveness of scheme fence		-	-0.070 (0.174)	-
Distance to urban centre	-	-	0.067 (0.171)	-0.436 (0.002)

Table 3. Spearman's rank correlation coefficients and exact probabilities (bracketed) of the associations between four performance indicators and selected characteristics of smallholder irrigation schemes in Vhembe

6.1 Operational status

The correlation between the operational status of smallholder irrigation schemes in Vhembe and hydraulic head was fairly strong (-0.618) and statistically highly significant. The negative correlation coefficient indicated that gravity-fed schemes were more likely to be (and remain) operational than pumped schemes. The correlation between operational status and irrigation method was even stronger (-0.707). This suggested that schemes employing micro irrigation were less likely to be operational than schemes using overhead irrigation. Schemes using surface irrigation were most likely to be operational but this was to be expected because on all gravity-fed schemes plot holders made use of the short furrow method to apply irrigation water.

6.2 Durability

The number of years schemes had operated, or had been in operation, before they collapsed, was very strongly correlated with hydraulic head (-0.848) and irrigation method (0.847). The negative sign of both correlations indicated that canal schemes were considerably more durable than pumped schemes. The positive, statistically significant ($p<0.01$) correlation between scheme area and number of years in operation and between number of plot holders and number of years in operation were probably the result of the co-variation of these two factors with hydraulic head. On average, the plot holder population on gravity-fed schemes (71) was slightly larger than on pumped schemes (63) and the average scheme area of gravity-fed schemes (83.4 ha) was also larger than that of pumped schemes (55.7 ha). The statistically significant ($p<0.05$) negative correlation between organisation of production and number of years in operation indicated that group projects were less likely to last than projects where plot holders farmed individually. Plot size did not appear to affect durability of irrigation schemes.

6.3 Cropping intensity

Associations between cropping intensity and scheme characteristics were not very strong. Of all the scheme characteristics that were tested, cropping intensity was most strongly correlated with water restrictions at scheme level ($r=-0.438$). This negative correlation, which was statistically highly significant ($p<0.01$), indicated that water restrictions, mostly due to seasonal differences in the supply of the source, inhibited farmers from using their plots as intensively as possible. The weak but statistically significant ($p<0.05$) negative correlation between the occurrence of water theft and cropping intensity was probably the result of water restrictions causing water theft and not due to differences in the degree of social order at the schemes. Hydraulic head, effectiveness of the scheme fence and distance to the nearest urban centre appeared not to affect cropping intensity. Cropping intensity tended to be positively correlated with irrigation method (micro irrigation > overhead irrigation > surface irrigation) but the correlation was not statistically significant ($p>0.05$). Surprisingly, cropping intensity was not associated with the presence or absence of cash based land exchanges among plot holders.

6.4 Degree of commercialisation

Associations between degree of commercialisation and scheme characteristics were also not strong. Of all the scheme characteristics that were tested, degree of commercialisation was most strongly correlated with distance to the nearest urban centre ($r=-0.436$). The relative strength of this correlation indicated that access to local urban markets was a significant factor in determining the orientation of production of plot holders on smallholder irrigation schemes. Remoteness, which reduced access to markets, resulted in farmers focussing more on producing for own consumption. Hydraulic head ($r=0.270$) and method of irrigation (0.373) were positively correlated with degree of commercialisation. This indicated that plot holders on pumped schemes tended to orient their farming more towards markets than those on gravity-fed schemes and that commercialisation was stimulated by the use of overhead and micro irrigation. Degree of commercialisation tended to be correlated positively with plot size, but this correlation was not statistically significant ($p>0.05$). It needs pointing out that among the schemes that featured in the analysis of degree of commercialisation, the range in average plot size among schemes was limited, with the smallest plots being 0.295 ha and the largest 2.197 ha. Water restrictions and the prevalence of cash-based land exchanges did not appear to affect degree of commercialisation.

7. Discussion

In this study it was demonstrated that gravity-fed canal schemes, on which farmers practised short furrow irrigation, were more likely to be operational and to last longer than pumped schemes. This was in line with the observations of Crosby et al. (2000) and Shah et al. (2002) for South Africa at large. They pointed out that pumped schemes tended to offer better quality irrigation than gravity-fed schemes and that pumping costs helped to impose financial discipline. However, they also stated that pumped schemes were more vulnerable to breakdown and that the cost of pumping tended to squeeze the net operating income of farm enterprises. An analysis of smallholder irrigation projects in Kenya concluded that pumped schemes operated and maintained by groups of smallholders were not sustainable (Scheltema, 2002). All of these projects had collapsed even before it was time to replace the pump, because of their higher financial and organisation requirement relative to gravity-fed schemes. The current study also indicated that pumped schemes were more vulnerable to flood damage than gravity schemes, mainly because during heavy flooding, pumps were washed away.

Generally, the cropping intensity on the smallholder schemes in the study area was well below the optimum values of 1.5 to 2.5 suggested by Faurès et al. (2007) but higher than the cropping intensity of 0.45 recorded by Mnkeni et al. (2010) at the Zanyokwe smallholder irrigation scheme in the Eastern Cape. Under conditions of adequate water supply, the subtropical climate of Vhembe puts the achievement of cropping intensities of 2 and more within reach. The study showed that water restrictions were a significant factor in determining cropping intensity. The water restrictions encountered on schemes in Vhembe were mostly seasonal and were caused by fluctuations in supply at source, in line with the prevailing summer rainfall pattern. Reductions in cropping intensity in response to water restrictions were also observed by Perry & Narayanamurthy (1998) in Asia. The absence of any evidence of an association between cropping intensity and cash-based land exchanges (rentals) among plot holders contradicted the assertion of Tlou et al. (2006) that land tenure was the most important system on system factor in irrigated agriculture. Other researchers have also suggested that the development of land rentals would increase cropping intensity on smallholder irrigation schemes in South Africa (Shah et al., 2002; Van Averbeke, 2008) but the results obtained in this study did not support this anticipated effect.

Degree of commercialisation on smallholder irrigation schemes in Vhembe was found to be associated with the location of schemes in relation to local urban centres. As distance between scheme and urban centre increased, farmers were less likely to produce for marketing purposes. Van Averbeke (2008) reported that marketing of farmer's produce at the Dzindi Canal Scheme, which also formed part of the current study, was mainly in the hands of street traders. Street traders purchased fresh produce from farmers in small quantities on a daily basis and most of them (66 of 84) were sedentary traders, who retailed this produce to the public in areas characterised by heavy pedestrian flows, such as the main streets in towns and townships and at the entrance of hospitals. The other 18 street traders were mobile. They retailed produce in villages and townships that surrounded Dzindi, carrying a bag of produce on their heads as they moved from door to door. Bakkie traders, who purchased produce in larger quantities and transported this produce in their vans to the same type of trading places as those of street traders, also purchased produce at Dzindi, but relative to street traders, they were less important. Nearly all 66 sedentary traders who purchased fresh produce at Dzindi used combi-taxis to transport their produce to their retail places and 54 of the 66 used taxis to get to the urban centre of Thohoyandou where they sold the produce. Taxi fares between Dzindi and Thohoyandou were relatively cheap, because of the short distance. Therefore, the negative correlation between degree of commercialisation and distance between scheme and nearest urban centre suggests that the cost of taxi fares could well be the factor that determines whether or not it is financially viable for sedentary street traders to purchase from scheme farmers and travel to urban centres to sell. During the field work it was noted that when schemes were located far away from an urban centre, farmers mainly sold produce to residents around the scheme, to mobile street traders, who retailed door to door and to bakkie traders. The absence of sedentary street traders purchasing fresh produce in these remote schemes, contrary to Dzindi, is a plausible explanation for the negative correlation between degree of commercialisation and distance to urban centres, which was also reported by Magingxa et al. (2009) for a sample of smallholder schemes in various other parts of South Africa.

8. Conclusion

The study of factors affecting the performance of smallholder irrigation schemes in Vhembe District yielded several interesting results, which have implications for smallholder irrigation scheme policy. Smallholder canal schemes were more likely to be operational and to last longer than pumped schemes. This finding questions the desirability of converting canal schemes into pumped schemes, which has been the practice of the RESIS Recharge Programme of the Limpopo Department of Agriculture. The study results suggest that rehabilitating existing canal systems would most probably be more sustainable. The study also indicated that in the absence of external interventions, commercialisation among farmers on smallholder schemes was more likely to occur when schemes were located close to urban centres, because proximity made it financially viable for street traders to travel between scheme, as the place of purchase, and town, as the place of retail, using public transport. This is important when the development of new schemes is being considered. For remote schemes, external intervention aimed at supporting market access appeared to be necessary to enhance commercialisation. At this stage, few of the farmer-managed schemes received marketing support from external agencies. Efforts to that effect are recommended and should be facilitated by public extension services in collaboration with the private sector. Finally, the study results indicated that the two smallholder irrigation schemes that were consolidated and farmed as single entities by a strategic partner (commercial farmer) were characterised by high cropping intensities and high degrees of commercialisation. However, the sustainability of this revitalisation trajectory is highly questionable. The introduction of centre pivot or floppy systems largely prevent plot holders from repossessing their schemes and farms as individuals once the joint venture arrangement comes to an end. As was already pointed out by Crosby et al. (2000), 'the worst scenario (for smallholder irrigation scheme development) is where central management not only takes all decisions unilaterally on a top-down basis but also conducts all on-farm operations'.

9. Acknowledgement

Research towards this chapter was conducted as part of the solicited WRC Project K5/1464/4, entitled, "Best Management Practices for Small-Scale Subsistence Farming on Selected Schemes and Surrounding Areas through Participatory Adaptive Research", which was initiated, managed and funded by the Water Research Commission (WRC) and the non-solicited WRC Project K5/1804/4, entitled, "Improving Plot Holder Livelihood and Productivity on Smallholder Canal Irrigation Schemes in Limpopo Province", that was managed and funded by the WRC. The author wishes to thank Mr J Denison for his valuable contribution to the design of the survey instrument, Mr K Ralivhesa for his assistance during the fieldwork, Mrs L Morey of the Biometry Division of the Agricultural Research Council for statistical analysis of the data and my daughter Lerato Van Averbeke for useful suggestions on how to improve the readability of the text. The contributions to the study made by smallholders on irrigation schemes in Vhembe and by staff of the Department of Agriculture in the Vhembe District and the Thulamela, Makhado, Musina and Mutale Municipalities are also gratefully acknowledged.

10. References

Aliber, M., & Hart, T. (2009). Should Subsistence Agriculture Be Supported as a Strategy to Support Rural Food Insecurity? *Agrekon*, Vol.48, No.4, (December 2009), pp. 434-458, ISSN 0303-1853

Backeberg, G.R. (2006). Reform of User Charges, Market Pricing and Management of Water: Problem or Opportunity for Irrigated Agriculture. *Irrigation and Drainage*, Vol.55, pp.1-12, ISSN 1531-0361

Backeberg, G.R., & Groenewald, J.A. (1995). Lessons from the Economic History of Irrigation Development for Smallholder Settlement in South Africa. *Agrekon*, Vol.34, No.3, pp. 167-171, ISSN 0303-1853

Beinart, W. (2001). *Twentieth Century South Africa*. Oxford University Press, ISBN 0-19-289318-1, Oxford, UK

Beinart, W. (2003). *The Rise of Conservation in South Africa: Settlers, Livestock and the Environments 1770-1950*. Oxford University Press, ISBN 978-0-19-926151-2, Oxford, UK

Bembridge, T.J. (1997). Small-Scale Farmer Irrigation in South Africa: Implications for Extension. *South African Journal of Agricultural Extension*, Vol.26, pp. 71-81, ISSN 0301-603X

Bembridge, T.J. (2000). *Guidelines for Rehabilitation of Small-Scale Farmer Irrigation Schemes in South Africa*, WRC Report No 891/1/00, Water Research Commission, ISBN 1-86845-683-8, Gezina, South Africa

Bembridge, T.J., & Sebotja, I. (1992). A Comparative Evaluation of Aspects of the Human Impact of Three Irrigation Schemes in Lebowa. *South African Journal of Agricultural Extension*, Vol.21, pp.30-41, ISSN 0301-603X

Bundy, C. (1988). The Rise and Fall of the South African Peasantry, Second Edition, David Philip, Cape Town, South Africa

Christie, F., & Hanlon, J. (2001). *Mozambique & The Great Flood of 2000*, James Currey, ISBN 0-85255-857-0, Oxford, UK

Commission for the Socio-Economic Development of the Bantu Areas within the Union of South Africa (1955). *Summary of the Report*, The Government Printer, Pretoria, South Africa

Crosby, C.T., De Lange, M., Stimie, C.M., & Van der Stoep, I. (2000). *A Review of Planning and Design Procedures Applicable to Small-Scale Farmer Irrigation Projects*, WRC Report No 578/2/00, Water Research Commission, ISBN 1-86845-688-9, Gezina, South Africa

De Lange, M., Adendorff, J., & Crosby, C.T. (2000). *Developing Sustainable Small-Scale Farmer Irrigation in Poor Rural Communities: Guidelines and Check Lists for Trainers and Development Facilitators,* WRC Report No. 774/1/00. Water Research Commission, ISBN 1-86845-692-7, Gezina, South Africa

Denison, J., & Manona, S. (2007). *Principles, Approaches and Guidelines for the Participatory Revitalisation of Smallholder Irrigation Schemes: Volume 2 – Concepts and Cases*, WRC Report No TT 309/07, Water Research Commission, ISBN 978-1-77005-569-8, Gezina, South Africa

De Wet, C. (2011). Where Are They Now? Welfare, Development and Marginalization in a former Bantustan Settlement in the Eastern Cape, In: *Reforming Land and Resource Use in South Africa: Impact on Livelihoods*, P. Hebinck & C Shacleton, (Ed.), 294-314, Routledge, ISBN 978-0-415-58855-3, Milton Park, Abingdon, UK

Economic Development Department (23 November 2010). The New *Growth Path: The Framework*. Available from http://www.info.gov.za/view/DownloadFileAction?id=135748

Fanadzo, M., Chiduza, C., Mnkeni, P.N.S., Van der Stoep, I., & Stevens, J. (2009). Crop Production Management Practices as a Cause for Low Water Productivity at Zanyokwe Irrigation Scheme. *Water SA* Vol.36, No.1, (January 2010), pp. 27-36, ISSN 1816-7950 (On-line)

Faurès, J-M., Svendsen, M., & Turral, J. (2007). Reinventing irrigation, In: *Water for Food Water for Life: A Comprehensive Assessment of Water Management in Agriculture*, D. Molden (Ed.), 353-394, Earthscan, ISBN 978-1-84407-396-2, London, UK

Houghton, D.H. (1955). *Life in the Ciskei: A Summary of the Findings of the Keiskammahoek Rural Survey 1947-51*, SA Institute of Race Relations, Johannesburg, South Africa

Inocencio,A., Kikuchi, M., Tonosaki, M., Maruyama, A., Merrey, D., Sally, H., & De Jong, I. (2007). *Cost and Performance of Irrigation Projects: A Comparison of Sub-Sharan Africa and Other Developing Regions*. IWMI Research Report 109, International Water Management Institute, ISBN 978-92-9090-658-2, Colombo, Sri Lanka

Kamara, A., Van Koppen, B., & Magingxa, L. (2001). Economic Viability of Small-Scale Irrigation Systems in the Context of State Withdrawal: The Arabie Scheme in the Northern Province of South Africa, *Proceedings of the Second WARSFA/Waternet Symposium: Integrated Water Resource Management: Theory, Practice, Cases*, pp. 116-128, Cape Town, South Africa, October 30-31, 2001

Khandlhela, M., & May, J. (2006). Poverty, vulnerability and the impact of flooding in the Limpopo Province of South Africa. Natural Hazards Vol. 39, pp. 275-287, ISSN 1573-0840 (electronic)

Lahiff, E. (2000). *An Apartheid Oasis? Agriculture and Rural Livelihoods in Venda*, Frank Cass, ISBN 0-7146-5137-0, London, UK

Laker, M.C. (2004*). Development of a General Strategy for Optimizing the Efficient Use of Primary Water Resources for Effective Alleviation of Rural Poverty*, WRC Report No KV 149/04, Water Research Commission, ISBN 1-77005-208-9, Gezina, South Africa

Leibbrandt, M., & Sperber, F. (1997). Income and Economic Welfare, In: *From Reserve to Region - Apartheid and Social Change in the Keiskammahoek District of (former) Ciskei: 1950-1990*, C. De Wet & M. Whisson (Ed.), 111-152, Institute for Social and Economic Research, Rhodes University, ISBN 0-86810-331-4, Grahamstown, South Africa

Letsoalo, S.S., & Van Averbeke, W. (2006). Water Management on a Smallholder Canal Irrigation Scheme in South Africa. In: *Water governance for Sustainable Development: Approaches and Lessons from Developing and Transitional Countries*, S. Perret, S Farolfi, & R. Hassan (Ed.), 93-109, Earthscan, ISBN-13 978-1-84407-319-1, London, UK

Lewis, J. (1984) The Rise and Fall of the South African Peasantry: A Critique and Reassessment, *Journal of Southern African Studies*, Vol. 11, No. 1, (October 1984), pp. 1-24, ISSN 0305-7070

Lipton, M. (1996). Rural Reforms and Rural Livelihoods: The Context of International Experience, In: *Land, Labour and Livelihoods in Rural South Africa, Volume One: Western Cape*, M. Lipton, M. De Klerk & M. Lipton, (Ed.), 1-48, Indicator Press, ISBN 1-86840-234-7, Dalbridge, Durban, South Africa

Makhura, M.T., Goode, F.M., & Coetzee, G.K. (1998). A Cluster Analysis of Commercialisation of Farmers in Developing Rural Areas of South Africa. *Development Southern Africa*, Vol. 15, No. 3 (Spring 1998), pp. 429-445, ISSN 0376-835X

Machethe, C.L., Mollel, N.M., Ayisi, K., Mashatola, M.B., Anim, F.D.K., & Vanasche, F. 2004. *Smallholder Irrigation and Agricultural Development in the Olifants River Basin of Limpopo Province: Management Transfer, Productivity, Profitability and Food Security Issues,* WRC Report No: 1050/1/04, Water Research Commission, ISBN 1-77005-242-9, Gezina, South Africa

Magingxa, L.L., Alemu, Z.G., & Van Schalkwyk, H.D. (2009) Factors Influencing Access to Produce Markets for Smallholder Irrigators in South Africa. *Development Southern Africa*, Vol. 26, No.1 (March 2009), pp 47-58, ISSN 0376-835X

Mills, M.E.E., & Wilson, M. (1952). *Land Tenure*, Shuter and Shooter, Pietermaritzburg, South Africa

Mnkeni, P.N.S., Chiduza, C., Modi, A.T., Stevens, J.B., De Lange, M., Adendorff, J., & Dladla, R. (2010). *Best management Practices for Smallholder Farming on Two Irrigation Schemes in the Eastern Cape and KwaZulu-Natal Through Participatory Adaptive Research*. WRC Report No TT 478/10, Water Research Commission, ISBN 978-1-4312-0059-7, Gezina, South Africa

Molden, D., Sakthivadivel, R., Perry, C.J., De Fraiture, C., & Kloezen, W.H. (1998). *Indicators for Comparing Performance of Irrigated Agricultural Systems*, IWMI Research Report 20, International Water Management Institute, ISBN 92-9090356-2, Colombo, Sri Lanka

Scheltema, W. (2002). Smallholder Management of Irrigation in Kenya, In. *The Changing Face of Irrigation in Kenya: Opportunities for Anticipating Change in Eastern and Southern Africa,* H.G. Blank, C.M. Mutero & H. Murray-Rust, (Ed.), 171-189, International Water Management Institute, ISBN 92-9090-475-5, Colombo, Sri Lanka

Shah, T., Van Koppen, B., Merrey, D., De Lange, M., & Samad, M. (2002). *Institutional Alternatives in African Smallholder Irrigation: Lessons from International Experience with Irrigation Management Transfer Management Transfer*, IWMI Research Report 60, International Water Management Institute, ISBN 92-9090-481-X, Colombo, Sri Lanka

Stayt, H.A. (1968). *The BaVenda*, Second Impression, Frank Cass, London, UK

Tlou, T., Mosaka, D., Perret, S., Mullins, D., & Williams, C.J. (2006). Investigation of Different Farm Tenure Systems and Support Structure for Establishing Small-Scale Irrigation Farmers in Long Term Viable Conditions, WRC Report No 1353/1/06, Water Research Commission, ISBN 1-77005-475-8, Gezina, South Africa

Tomlison Commision (1955) see Commission for the Socio-Economic Development of the Bantu Areas within the Union of South Africa

Turral, H., Svendsen, M., & Faurès, J.M. (2010). Investing in Irrigation: Reviewing the Past and Looking to the Future. *Agricultural Water Management*, Vol. 97, pp. 551-560, ISSN 0378-3774

Umhlaba (2010). *A Review of Experiences of Establishing Emerging Farmers in South Africa: Case Lessons and Implications for Farmer Support within Land Reform Programmes*, Food and Agricultural Organization of the United Nations, ISBN 978-92-5- 106490-5, Rome, Italy

Van Averbeke, W. (2008). *Best Management Practices for Small-Scale Subsistence Farming on Selected Irrigation Schemes and Surrounding Areas through Participatory Adaptive Research in Limpopo Province*, WRC Report No TT 344/08, Water Research Commission, ISBN 978-1-77005-689-3, Gezina, South Africa

Van Averbeke, W., & Hebinck, P. (2007). Contemporary Livelihoods, In: *Livelihoods and Landscapes: The People of Guquka and Koloni and their Resources*, P. Hebinck & P.C. Lent, (Ed.), 285-306, Brill, ISBN 978-90-04-16169-6, Leiden, The Netherlands

Van Averbeke, W., M'Marete, C.K., Igodan, C.O., & Belete, A. (1998). *An Investigation into Food Plot Production at Irrigation Schemes in Central Eastern Cape*, WRC Report No 719/1/98, Water Research Commission, ISBN 1-86845-334-0, Gezina, South Africa

Van Rooyen, C.J., & Nene, S. (1996). What can we learn from Previous Small Farmer Development Strategies in South Africa? *Agrekon*, Vol. 35, No. 4 (December 1996), pp. 325-331, ISSN 0303-1853

Vermillion, D.L. (1997). *Impacts of Irrigation Management Transfer: A Review of the Evidence*, Research Report 11, International Irrigation Management Institute, ISBN 92-9090-340-5, Colombo, Sri Lanka

Vink, N., & Kirsten, J. 2003. Agriculture in the National Economy, In: *The Challenge of Change: Agriculture, Land and the South African Economy*, L. Nieuwoudt & J Groenewald (Ed.), 3-19, University of Natal Press, ISBN 1-86914-032-X, Pietermaritzburg, South Africa

Vink, N., & Van Rooyen, J. (2009). *The Economic Performance of Agriculture in South Africa since 1994: Implications for Food Security*. Development Planning Division Working Paper No 17, Development Bank of Southern Africa, Halfway House, South Africa

22

Decision Strategies for Soil Water Estimations in Soybean Crops Subjected to No-Tillage and Conventional Systems, in Brazil

Lucieta G. Martorano[1], Homero Bergamaschi[2], Rogério T. de Faria[3] and Genei A. Dalmago[4]
[1]*Embrapa Amazônia Oriental*
Travessa Eneas Pinheiro s/n, Belém, PA
[2]*UFRGS and CNPq, P. Alegre, RS*
[3]*FCAV-Unesp, Jaboticabal, SP*
[4]*Embrapa Trigo*
Passo Fundo, RS
Brazil

1. Introduction

Conservationist practices have been increasingly adopted in Brazil during the last thirty years, especially with the change from the conventional cropping system to the no-tillage system. The latter has been widely spread in several Brazilian regions where the soybean crop takes part in annual crop rotation (Denardin et al., 2005). In the Center-Southern region it reached nearly 80% of grain producers. Among environmental and economic gains are: increasing crop yield, soil water and carbon stocks increments, reductions of production costs, control of soil erosion, mitigation of carbon emissions and water crop deficit. According to Buarque (2006) sustainable agriculture involves several structural changes and faces social and political resistance. In order to mitigate environmental impacts on food production and ecosystem services, policies should aim to develop more resilient cropping systems and provide sustainable management of natural resources.

Soybean is a commodity of great interest in national and international markets of which Brazil is the second largest producer in the World. Climate variability can severely affect crop yield and reduce total food production. Soybean production has proved to be highly dependent on climate to achieve genetic potential of the cultivars used by farmers. Among climate variables, studies in Rio Grande do Sul State, in Southern Brazil, showed that soybean production was mostly correlated with rainfall. Interannual variability in rainfall has been considered the main cause of fluctuations in grain yields (Bergamaschi et al., 2004) for non-irrigated crops.

Periods of water deficits from January to March are frequent and usually coincide with the summer crop critical period (flowering and grain filling), limiting the yield of soybean in the state (Matzenauer et al., 2003).

Decision support systems, such as DSSAT (Decision Support System for Agrotechnology Transfer) can be very useful for cropping system planning. The models included in that software were calibrated for different climate and soil conditions and crop management system and also applied by researchers worldwide (Jones et al., 2003). Different physical and physiological processes are simulated by the DSSAT models, such as photosynthesis, respiration, biomass accumulation and partitioning, phenology, growth of leaves, stems and roots (Hoogenboom, 2000, Hoogenboom et al., 2003), and soil water extraction (Faria & Bowen, 2003). After calibration at a site in the state of Rio Grande do Sul, Brazil, the model CROPGRO-Soybean showed a high performance to simulate grain yield and crop growth and variables of development under the no-tillage cropping system and the conventional system (Martorano, 2007; Martorano et al., 2007; Martorano et al., 2008a; Martorano et al., 2008b; Martorano et al., 2009). DSSAT is frequently updated (v4.5 is on http://www.icasa.net), and currently there is a group of researchers working on the calibration of DSSAT/ CENTURY in order to assist in decision strategies.

This chapter presents experimental results used in the assessment of the performance of the DSSAT models, carried out in a site in Rio Grande do Sul, Brazil. This study aimed at the establishment of scenarios for sustainable agriculture, based on principles of data interoperability and DSSAT users' network tools.

2. Problems and strategies for soybean crops

Several factors should be considered when evaluating low carbon agriculture, for example, the land use and agricultural management, the correct crop conduction, the evaluation of edapho-climatic characteristics, ethnic and cultural respect, and the aggregation of goods and services to the society. Some studies on sustainability indicators have pointed out that cropping systems, such as the no-tillage system, reduce environmental impacts, improve productivity and have lower production costs. Global climate projections show that temperature increases in some areas with high temperatures could worsen food production problems. Variation in productivity due to water availability is already a common problem for rain fed crops, which are the majority of crop areas in Brazil.

The Brazilian economy is closely linked to the supply of natural resources, especially water use, in agriculture, hydropower generation, industrial sectors, and other human demands. However, the lack of water management may cause several impacts and serious threats to the human population. It is known that water has plenty sources in many regions of Brazil, but this resource may become scarce if there is no concern regarding its maintenance.

Awareness of appropriate use in different segments of the productive sector is indispensable to enable quantifying the "water footprint" (Hoekstra & Chapagain, 2007), in these sectors. For agriculture, the concerns have turned toward waste of water, not only in arid regions of the world, but also the waste related to improper use and decisions on when, how and what is the most efficient technology to be applied in irrigated crops, for instance.

Decision support tools, such as DSSAT (Decision Support System for Agrotechnology Transfer), show high potential for decision makers to improve management of soybean crops in Brazil, after calibration of the models. Martorano (2007) and Martorano et al (2008a) showed that the CROPGRO-Soybean model had high performance simulating phenological phases, growth and yield under irrigated condition, both in conventional tillage and no tillage. DSSAT models can be a suitable tool to assess the effects of tillage on soil carbon in order to mitigate carbon emissions to the atmosphere (Martorano et al, 2008b). The model can simulate realistic scenarios for decision-makers (farmers, managers, agricultural technicians and government), as well as to identify crops problem for scientists defining research priorities.

3. Material and methodology

An example of research on soil water status is presented based on a field experiment. To evaluate soil-plant-atmosphere processes associated with soil management on the express condition of water, an experiment was conducted in the cropping season of 2003/04 with soybeans (cv. Fepagro RS10, long cycle), at the Experimental Station of the Federal University of Rio Grande do Sul State (EEA/UFRGS), in Eldorado do Sul, Brazil (30º 05'27"S; 51º 40'18" W, altitude 46m). The experiment was sown on 2003, Nov 20 in a typical dystrophic red clay soil, with plots conducted under no-tillage (NT) and conventional tillage (CT), irrigated (I) and not irrigated (NI).

Crop was sown 0.40 m between rows, with an average population of 300,000 plants ha^{-1}. An automatic meteorological station recorded weather variables and tensiometers (mercury-Hg column) measured daily soil water matric potential. Weekly assessment on plant growth and development were taken (Fig. 1). Leaf area index (LAI) and dry biomass (leaves, stems, pods and seeds) were determined weekly. Model input included minimum and maximum air temperature (°C), precipitation (mm) and solar radiation (MJ m^{-2}). Soil inputs included soil classes, soil physical-hydraulic and chemical properties, in addition to crop management information (weed control, variety, planting date and irrigation).

Irrigation was applied when soil matric potential reached -60 kPa, as measured by tensiometers installed in irrigated no-tillage plots (NIT). The crop water use was monitored by a weighing lysimeter cultivated with soybean under conventional tillage. Each management system contained two batteries with tensiometers placed at depths (m) of 0.075, 0.15, 0.30, 0.45, 0.60, 0.75, 0.90 and 1.05 m and one with the same depths in addition to a tensiometer at 1.20m. Readings were made every day, around 9 p.m. (local time).

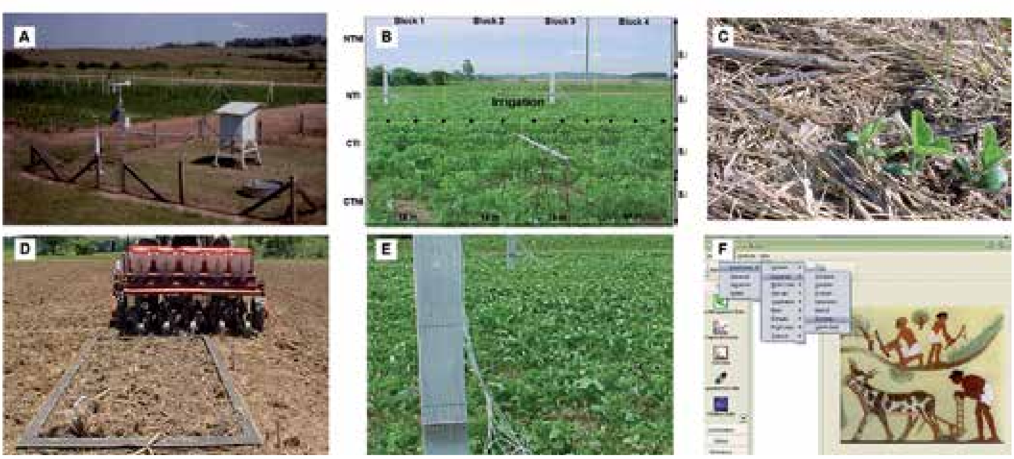


Fig. 1. Meteorological station (A), experimental design (B), soybean in no-tillage system (C), lysimeter (D), batteries with tensiometers (E) in experimental area at the EEA / UFRGS, 2003/04, in Rio Grande do Sul State, Brazil, and layout of software DSSAT initial page (F).

With matric potential values, the corresponding soil moisture was calculated using the soil retention curves obtained experimentally by Dalmago (2004) for no-tillage and conventional tillage plots. The program of Dourado Neto et al. (2005) was used to calculate the volumetric water content (Soil Water Retention Curve-SWRC, v.1.0), using Equation 1, Van Genuchten (1980):

$$\theta v = \theta r + \frac{(\theta s - \theta r)}{\left[(1 + \alpha \Psi m)^n\right]^m} \tag{1}$$

where the volumetric water content ($cm^3\ cm^{-3}$) is represented by the θv and humidity and residual saturation θr and θs, respectively. The matric potential of soil water (kPa) is represented by Ψm and coefficients (dimensionless) by the letters α, n and m.

In Decision Support System for Agrotechnology Transfer was considered an experimental data of soil, climate and specifications of soil management. The model selected for the legume was CROPGRO Soybean. In this chapter, attention turned to the evaluation of model performance to simulate soil water content. CROPGRO-Soybean was calibrated, using genetic coefficients for the cultivar Fepagro RS-10, as described by Martorano (2007) and Martorano et al (2008a). The methodology of Willmott et al. (1985) recommended the use of RMSE (root mean square error) and D-index (index of agreement), but suggested that RMSE is the ''best'' measure as it summarizes the mean difference in the units of observed and predicted values (Martin et al., 2007). The RMSE indicates the bias produced by the model, i.e., deviation of the actual slope from the 1:1 line while it also may be seen as a precision measure, as it compares the bias of model predicted values with the random variation that may occur. The D-index is a descriptive (both relative and bounded) measure, and can be applied to make cross-comparisons between observed and simulated data (Loague & Green, 1991) by equation 2 and 3.

$$D = 1 - \left[\frac{\sum_{i-1}^{N} (Pi - Oi)^2}{\sum_{i-1}^{N} \left(|P'i| + |O'i|\ \right)^2}\right] \tag{2}$$

where N is the total of observations, Pi and Oi are respectively predicted and observed values , P'i refers to the absolute difference between Pi and the average of predicted variable P, and O'i is the difference between the observed value Oi and the average of observed variable O. The closer to unity is the D-index (Willmott et al., 1985), the higher the index of agreement between observed data and simulated value by the model is. Also, the observed data were compared with those simulated with the mean square error (RMSE), using equation 3.

$$RMSE = \sqrt{\frac{\sum_{i-1}^{N} (Pi - Oi)^2}{N}} X \frac{100}{M} \tag{3}$$

where Pi and Oi are the values of the variables simulated by the model and observed in the field, corresponding to the evaluation interval. The RSME expresses the relative difference

(%) between observed and simulated by CROPGRO-Soybean. It is considered highly accurate when the RMSE is less than 10%, good precision between 10% and 20%, and between 20% and 30%, which depending on the boundary condition may be acceptable. The model showed low accuracy when error is above 30%.

In this chapter, attention is given to evaluating the model performance for simulating the soil water content. The mean square error (RMSE) was used to expresses the relative difference (%) between the observed data and estimations by CROPGRO-Soybean, as described by Martorano (2007) and Martorano et al (2008a).

According to data from soil water content and grain yield was applied analysis of variance and means were compared using the Tukey test at 5% significance level.

4. Results and discussion

Evaluating the meteorological information during the soybean cycle (cv. Fepagro RS-10) showed that solar radiation ranged between 8.8 and 27.9 MJ $m^{-2}day^{-1}$ (Fig. 2), and the average of 20.7 MJ $m^{-2}day^{-1}$, corroborate with the climate average for the period in the region which is about 20 MJ $m^{-2}day^{-1}$ (Bergamaschi et al., 2003). There were two solar radiation peaks; one in January, the first ten-day period of (J_1), the order of 27 MJ m^{-2} day^{-1}, and another in March, the second ten-day period (M_2) close to 25 MJ m^{-2} $days^{-1}$. These values corroborate with those presented by Cargnelutti Filho et al. (2004), which indicate that in Rio Grande do Sul, the highest averages of solar radiation for 10-day-periods occur during December and January. Regarding the total rainfall, 663.4 mm were computed during the soybean cycle, with two moments of rain shortage of supply.

As showed in Figure 2, it was observed that in the three first ten-day periods, the total amount of water in the 2003/04 agricultural year was above the climatological normal. In November, the third ten-day period, and in December the first ten-day period, rainfall amounted around 60 mm and the second ten-day period in December was close to 140 mm, exceeding the normal rainfall value (100 mm) observed in time series. In December the third ten-day period and in January the first ten-day period showed less rain supply, making it the first moment of water scarcity.

According to Table 1 values, when the crop was at early flowering (R_1), the air temperature was higher but remained below 35° C and the minimum was above 10°C. At the end of the soybean cycle (cv. Fepagro RS-10), there were 1945.1 accumulated degree days (ADD). Meteorological conditions at the experimental site for main phenological stages of soybean crop (Table 1), according to Fehr & Caviness (1977).

In some crops, changes in phenological stages depend basically on temperature. For soybean crops, high air temperature during the growth stage reduce time for the flowering phase (Major et al., 1975). Under tropical and subtropical conditions, low temperatures limit severely plant growth, that have photosynthetic capacity reduced due to the drop of quantum efficiency of Photsystem II as well as reduced activities of Photosystem I. There is also decrease in cycles of synthesis of stromal enzymes in C_3 plants (Allen & Ort, 2001).

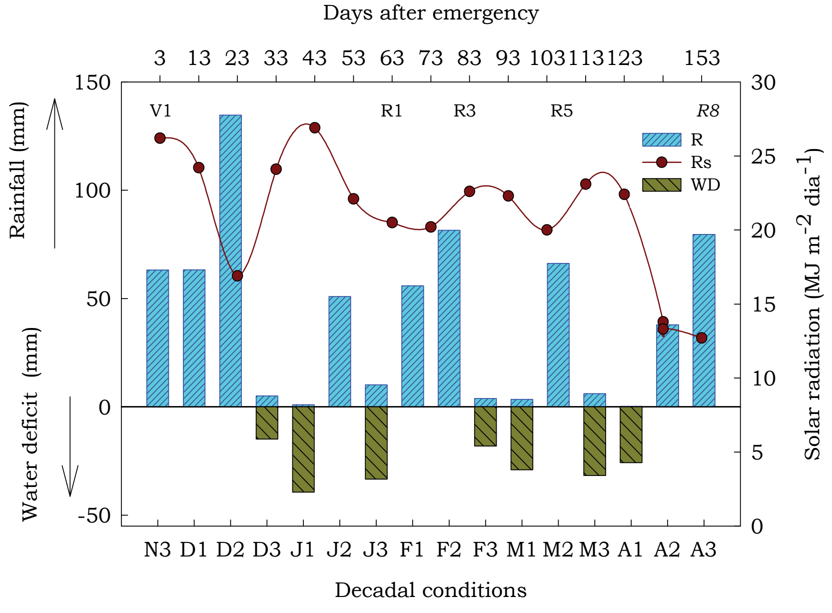


Fig. 2. Rainfall (R), solar radiation (Rs) and water deficit (WD) for ten-day periods during the soybeans cycle in the 2003/04crop year, in Eldorado do Sul, Brazil.

Growth stages	Rs	R	Air temperature (°C) (Average)			ADD	WD (mm)	
	MJ m^{-2} dia^{-1}	(mm)	Tmax	Tmin	Tave	Tb (10°C)	CTNI	NTNI
S - V_{11}	22.6	328.5	28.5	16.4	22.5	789.6	101.2	93.7
V_{11} - R_1	20.1	0.0	34.3	19.4	26.9	806.5	3.1	3.5
R_1 - R_5^*	21.8	141.2	29.4	16.5	22.9	1259.6	102.1	113.4
R_5^{**} - R_7	19.2	76.1	29.3	17.1	23.2	1814.4	80.2	72.3
S - R_8	**20.6**	**663.4**	**28.6**	**16.3**	**22.5**	**1945.1**	**287.5**	**280.9**

Rs (Global solar radiation), R (rainfall), Tmax, Tmin, Tave (maximum, minimum and average air temperature), WD (water deficit). S (sowing), R_1 - beginning of flowering, R_5*- first day on R_5 period (beginning of grain filling); and R_5** - period between the second day on R_5 and the first day on R_7 (physiological maturity) and R_8 (complete maturity), ADD (accumulated degree-days calculated in Celsius unit, from seedling emergency on Nov.27.2003 to the end of cycle on Apr.30.2004). Tb is minimum base temperature for soybeans, 10°C.

Table 1. Meteorological parameters during the soybean cycle (cv. Fepagro RS-10) in different growth stages (Fehr & Caviness, 1977), in non-irrigated conventional tillage (CTNI) and no-tillage (NTNI). EEA / UFRGS, Eldorado do Sul, Brazil, 2003/04.

The results obtained in the field experiments showed that maximum evapotranspiration (ETm) amount during the cycle of soybeans was 681.3 mm, with a daily average of 4.5 mm day^{-1}. In the period between the late vegetative stage (V_{11}) and early grain filling (R_5), the highest evapotranspiration rates (6 to 8.0 mm day^{-1}) were observed between 49 and 93 DAE, with degree-days ranging between 789.6 and 1259.6. These rates reflect the condition of the irrigated crop in conventional tillage (lysimeter area) and maximum leaf area index (6.3), obtained in fully flowering (R_2).

It was observed in Martorano et al (2009) that on Dec 23.2003, the soil under conventional tillage systems without irrigation (CTI) contained 0.236 cm^3 cm^{-3} of moisture in the superficial layer (0.075m), indicating the beginning of drying, which was only observed in no-tillage irrigated (NTI) on Dec.25.2003, when soil water content was 0.270 cm^3 cm^{-3}. These data indicated the anticipation of the soil drying under conventional system compared to no-tillage. On Dec.26.2003, the soil was 0.185 cm^3 cm^{-3} in CTI and there was disruption of mercury columns of tensiometers on the most superficial layer (0.075 m), which was only observed in no-tillage on Dec.29, 2003, reinforcing the evidence of higher water storage in the upper layers in no-tillage systems.

In the subsequent depth of 0.15 m, the tensiometers Hg-columns disrupted in plots under conventional system on Dec.28.2003, while in no-tillage this fact occurred only on Jan.03.2004, showing that there is anticipation in soil drying front under conventional systems compared to no-tillage (Fig.3). By analyzing all the soil profile, observed that there was more rapidly advancing drying front in conventional system compared to no-tillage. In this first period of drying, the crop was in its growing period, and monitoring of plant responses to water conditions was focused on the second moment of less rainfall.

The second period of water shortage was from February, coinciding with the flowering and grain filling (from R_1 to R_5 stages), considered as critical in terms of water requirement for soybean crops (Berlato & Fontana, 1999). In this aspect, Martorano et al. (2009) showed the pattern of drying soil, indicating that the matric potential in the conventional system were more negative in relation to the no-tillage system. From 0.45 to 0.90 m of soil depth in the no-tillage and from 0.30 to 1.05 m in the conventional system, the soil remained drier than in the rest of the profile, probably due to a greater concentration of roots in these soil layers than in the surface layer, resulting from the tap root system of soybeans (Fig. 4). At 0.30 m deep, the matric potential in no-tillage was higher than -0.03 MPa, which was less negative than in the conventional system, around -0.05 MPa (Fig.5).

It is known that less soil moisture may place restrictions on water transfer to the atmosphere, not only influenced by the weather, but also by factors such as the root system, cultivar, management system, phytosanitary conditions and soil characteristics. For the conditions of the experiment, the main limiting factor was the reduction in water supply by rainfall, leading to periods of water deficit. The irrigated water treatment presents a brief discussion of the dynamics of soil water by simulated CROPGRO-Soybean and observed in field experiment showing the performance of the tool to simulate soil drying times. Fig. 6 shows that the moisture in the soil between 0.05 and 0.15 cm depths had differences management systems, indicating that no-tillage values showed higher humidity compared to conventional tillage irrigated condition, confirming the studies of Dalmago (2004) on the dynamics of drying the soil in these two management systems.

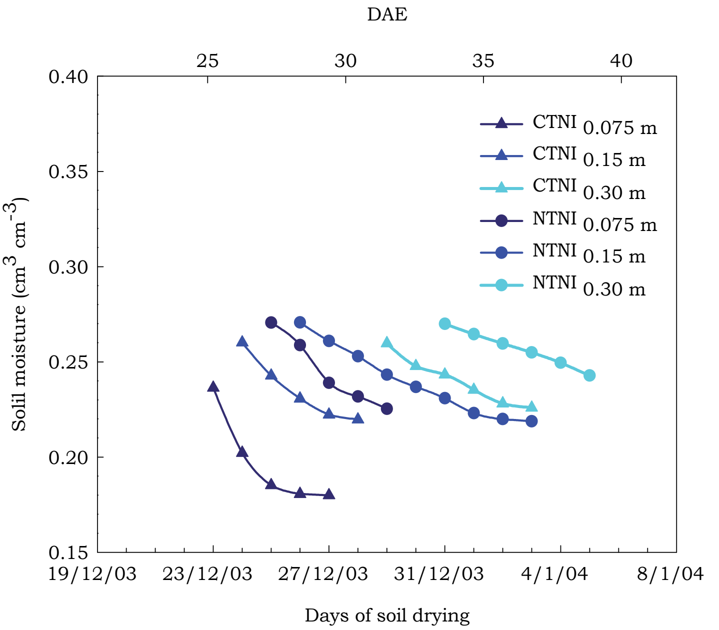


Fig. 3. Soil moisture in functions of days of soil drying and days after soybean plants emergence (DAE) under non-irrigated conventional tillage (CTNI) and no-tillage system (NTNI), in depths between 0.075 m and 0.30 m. Eldorado do Sul, Brazil, 2003/04, Brazil.

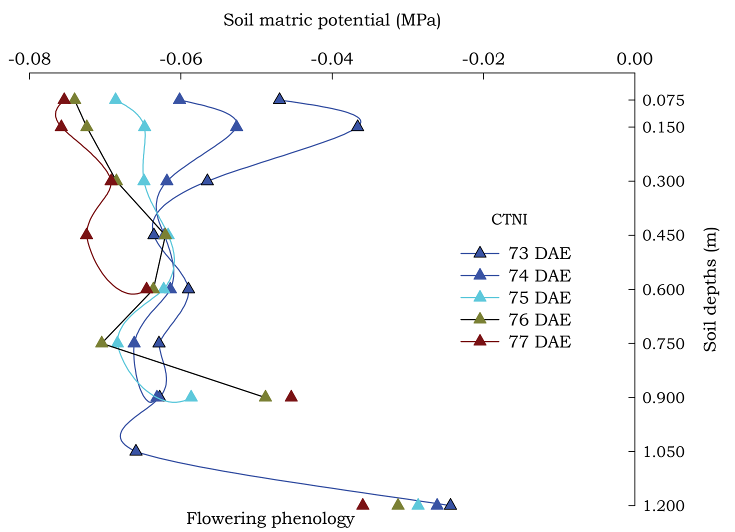


Fig. 4. Soil water matric potential in soybean crops under non-irrigated conventional system (CTNI) from 0.075 m to 0.30 m depths, at different days of soil drying, in Eldorado do Sul, Brazil, 2003/04.

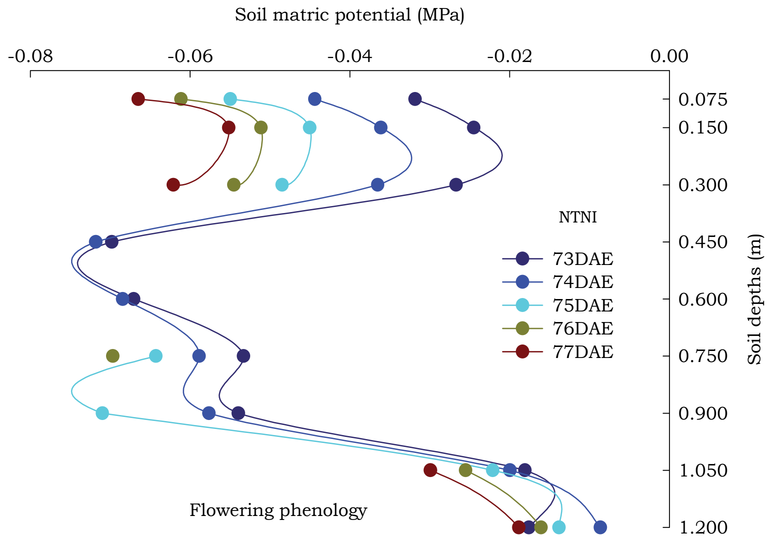


Fig. 5. Soil water matric potential in soybean crops under non-irrigated no-tillage system (NTNI), from 0.075 m to 0.30 m depths, at different days after plants emergence, in Eldorado do Sul, Brazil, 2003/04.

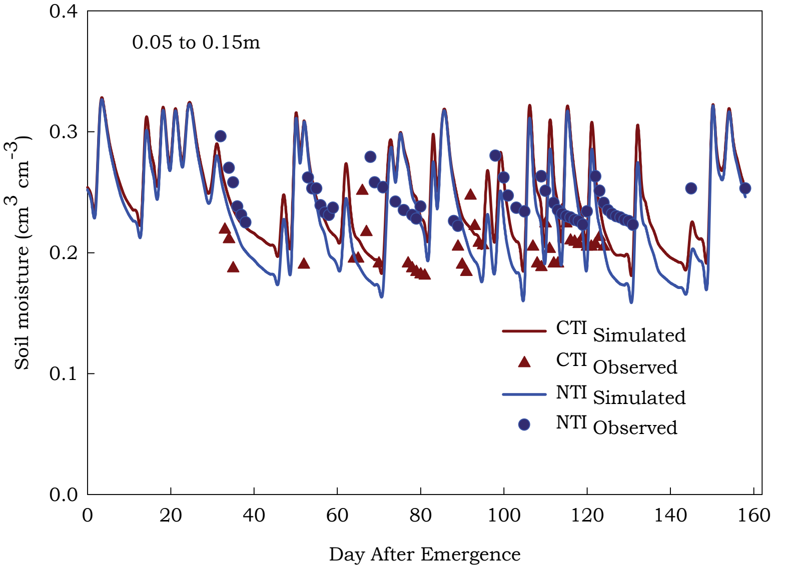


Fig. 6. Observed and simulated volumetric soil moisture at depths of 0.05 m and 0.15 m, in soybean crops under irrigated conventional tillage (CTI) and irrigated no-tillage (NIT) systems. Eldorado do Sul, Brazil, 2003/04.

In conventional tillage non-irrigated the model's ability was very low (32%), and no-tillage non-irrigated about 27% the value for the square root of the mean error, reinforcing the evidence of need for adjustments in routines or subroutines in the model to improve predictions of soil moisture levels.

According to Martorano et al (2007), the CROPGRO-Soybean was highly efficient in simulating the storage of soil water between 0.15 m and 0.30 m in conventional tillage and non-tillage irrigated. It was observed that in irrigated conventional tillage the model had high performance, with minimum distance between the simulated and observed (Fig. 7). The RMSE was 22.4% and in no-tillage irrigated (NTI) it was about 11%, which was considered a good precision of the model simulating water conditions in both systems adopted by farmers, showing that the tools can be use in management strategies in crops. The D-index of agreement (Willmott et al., 1985) in irrigated non-tillage (NTI) was 0.95, while the irrigated conventional tillage (CTI) had also a high level of agreement, 0.92, indicating high agreement closer to the 1:1 line (Fig. 7).

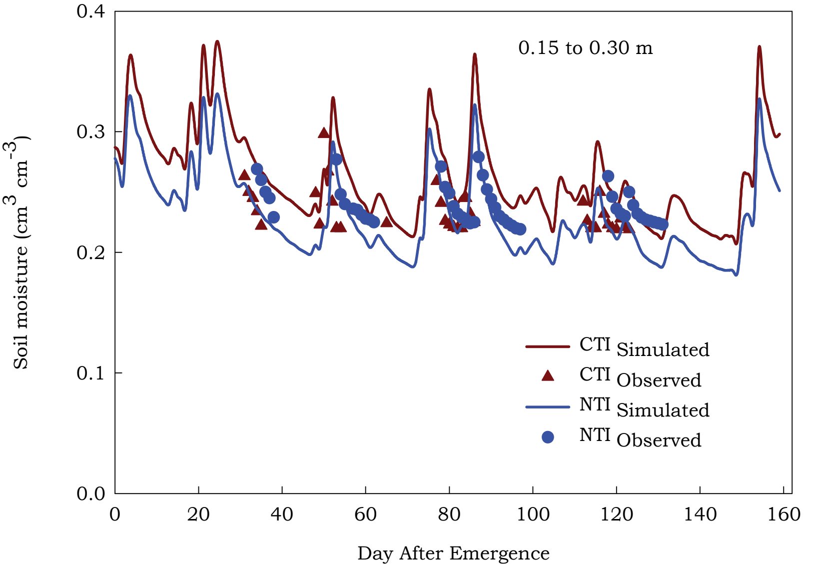


Fig. 7. Simulated soil moisture by CROPGRO-Soybean and observed in the layer between 0.15 and 0.30 m depths, in irrigated (I) plots of conventional tillage (CT) and no-tillage system (NT). Eldorado do Sul, Brazil, 2003/04.

In the same depth of non-irrigated treatments, the error (RMSE) in CTNI was 24.4% (which, depending on the boundary condition, may be acceptable) and NTNI was 19.0% in that limit, indicating good precision and accuracy of model, which can be used to simulate in this layer (Fig. 8). In irrigated conventional tillage the simulated values for the layers of 0.30 and 0.45 m depth may be considered acceptable presenting a 19.2% error (RMSE). In irrigated no-tillage it was 22.1% which, depending on the boundary condition, may be acceptable (Fig. 9).

In assessing the performance of CROPGRO for soybeans, after calibration of parameters such as hydraulic conductivity and root system depth in 224 points in 16 ha, using performance data for three years in Iowa, in the United States of America, Paz et al (1998) found that water stress explained 69% of income at all points measured, indicating the importance of adjustments in the soil parameters in crop yield simulations. In this sense, to increase the performance of CROPGRO Soybean tillage it is necessary to adjust the parameters that simulate the limits of water retention in soil, capable of simulating the water supplies observed in the field, which determine water reserves income grain, in periods of soil drying.

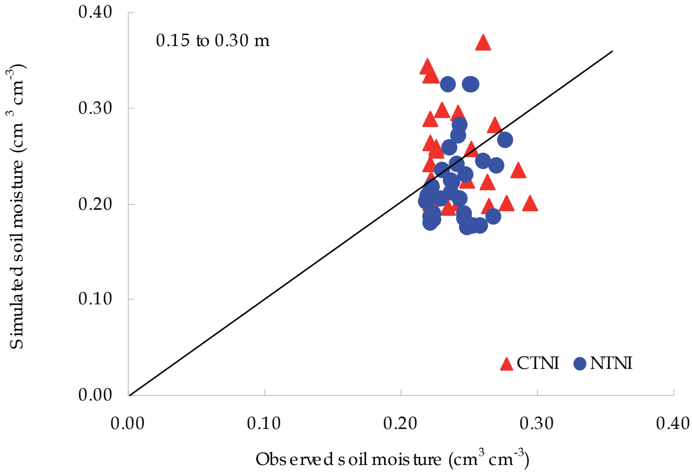


Fig. 8. Simulated soil moisture by CROPGRO Soybean and observed in a field experiment on non-irrigated conventional tillage (CTNI) and non-tillage (NTNI) systems, in the 0.15 to 0.30 m depths. Eldorado do Sul, Brazil, 2003/04.

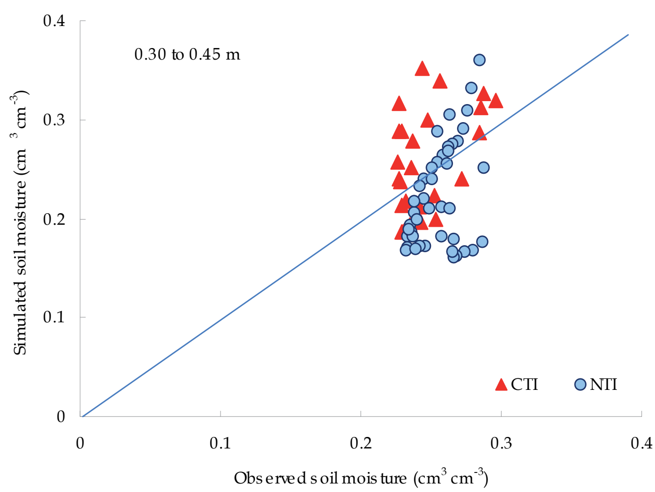


Fig. 9. Simulated soil moisture by CROPGRO Soybean and observed in a field experiment on irrigated conventional tillage (CTI) and non-tillage irrigated (NTI) systems in depths from 0.30 to 0.45 m. Eldorado do Sul, Brazil, 2003/04.

The model presented better performance in conventional tillage, simulating both the stock of water in the soil for growth and development and yield of soybean, than in the no-tillage system. The model simulations penalize indicators of growth and yield under no-tillage, regardless of the culture water status. The low and middle performance of the CROPGRO Soybean model for simulating the soil water inventories indicates that there is need for adjustments to the parameters that simulate the limits of water retention in soil, capable of simulating moisture observed in the field tillage.

Observing responses in the plant under no-tillage, in terms of growth and yield components, reinforce the effects of the water supply system during periods of dry soil. The comparison between observed and simulated data, through the CROPGRO-Soybean model, showed high accuracy of the simulated crop phenological stages, as demonstrated by the low scattering of points around the 1:1 line (Fig. 10), mostly for treatments with irrigation. These results may allow an efficient performance of the model in simulating the crop phenology (D-Index ≈ 1) and for estimating the canopy biomass.

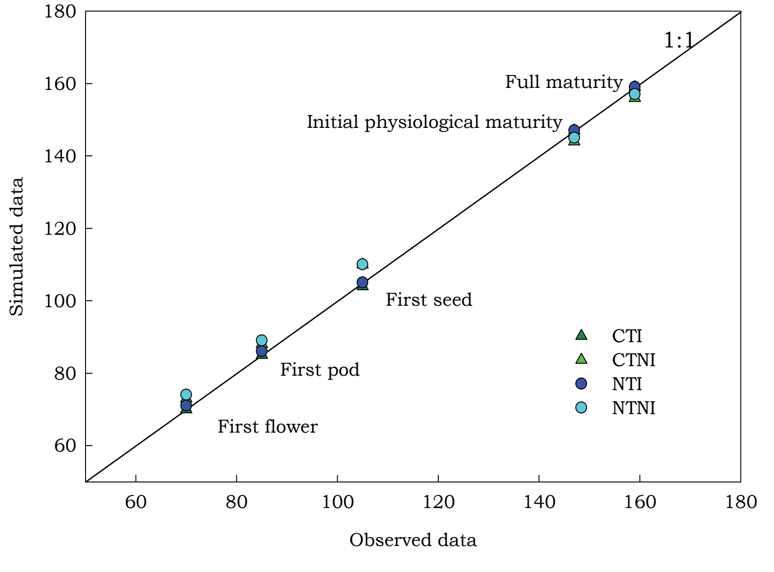


Fig. 10. Simulated by CROPGRO-Soybean model and observed phenological stages (in days after sowing) in CTI (irrigated conventional tillage), CTNI (non-irrigated conventional tillage), NTI (irrigated no-tillage) and NTNI (non-irrigated no-tillage) in Eldorado do Sul, Brazil, 2003/04.

Plant emergence occurred eight days after sowing (DAS) and the beginning of flower appearance was about 71 days after emergence, with a three-day difference between irrigated and non-irrigated treatments. In conventional tillage with irrigation, the comparison between simulated and observed data showed "D-Index" values corresponding to 0.83 for LAI, 0.96 for plant height, 0.93 for leaf weight, 0.97 for total dry biomass, 0.90 for pod weight and 0.98 for seed weight. In no-tillage system with irrigation, "D-Index" values were 0.82, 0.87, 0.89, 0.94, 0.88 and 0.91, respectively.

The model had lower accuracy under water deficit (non-irrigated treatments), especially in the no-tillage system. Regarding crop grain yields, the observed data were 3,597 kg ha^{-1} (irrigated conventional tillage), 3,816 kg ha^{-1} (irrigated no-tillage), 1,559 kg ha^{-1} (non-irrigated conventional tillage) and 1,894 kg ha^{-1} (non-irrigated no-tillage). The simulated grain yields by the model were 3,108 kg ha^{-1} (irrigated conventional tillage), 2,788 kg ha^{-1} (irrigated no-tillage), 824 kg ha^{-1} (non-irrigated conventional tillage) and 818 kg ha^{-1} (non-irrigated no-tillage).

5. Future research prospective

In order to increase efficiency of water used by plants, tools like DSSAT have been developed to help farmers with soil crop and water management planning. Researches on this tools applied to field experiments have shown that it is necessary to adjust models capable of simulating available water storage in the soil, especially in no-tilled cropping areas, for increasing the accuracy of simulations of the plant growth and grain yields of soybean by the CROPGRO-Soybean routines for soil water modeling (Faria & Madramootoo, 1996, Faria & Bowen, 2003) and soil C sequestration of DSSAT/CENTURY (Tornquist et al, 2009 a e b, Basso et al., 2011).

The models calibrated to deal with the soil system management have great potential to help developing ecologically efficient strategies related to water restitution in the soil, reducing the "Water Footprint" in irrigated tillage, increasing efficiency in food producing (FAO, 2006, FAO, 2009) and reducing agriculture water waste. Agrometeorological assessments help agricultural precision by indicating the right moment for water replacement during the crop phenological stages which are more vulnerable to water stress conditions.

On the other hand, impacts of climate changes related to water cycles, such as occurrence of extreme events and water supply for agriculture, represent major concerns for scientists and stakeholders dealing with environmental, social and economical analysis in different countries around the world. Particularly, the Brazilian economy is closely linked to the supply of natural resources, especially water use, both in agriculture and in hydropower generation, industrial sectors, and human consumption. The lack of adequate water management and planning can cause serious threats to human population. Although, there is plenty of drinking water in many regions of Brazil, this resource may become scarce if there is not any concern about the maintenance of water related ecosystem services. Major world problems occur due to impacts caused by human actions that disrespect the carrying capacity of natural environments.

Awareness of appropriate use by different productive sectors is indispensable to establish sustainable water management in economical activities. Water management should include monitoring and modeling schemes to assess the impact of economical activities on water sustainability, for instance, by using the "water footprint" approach to quantify agricultural water use for a particular product (Hoekstra & Chapagain, 2007). For agriculture, the concerns have turned toward water waste, and not only water scarcity in more arid regions of the world. Waste of water occurs due to improper decisions on water use, such as when, how and what is the most efficient technology to be applied in irrigated crops. Water deficit associated with periods of prolonged drought during the rainy season are a major cause of failed crops of grain in Brazil, especially in states in the Centre-South and Northeast.

Soil C sequestration (Lal, 2004) is reversible, as factors like soil disturbance, vegetation degradation, fire, erosion, nutrients shortage and water deficit may all lead to a rapid loss of soil organic carbon. It's the mechanism responsible for most of the mitigation potential in the agriculture sector, with an overall estimated 89% possible contribution to the technical potential (IPCC, 2007) excluding, however, the potential for fossil energy substitution through non agricultural use of biomass. There is a paucity of studies integrating soil C sequestration in the GHG balance of pastures and livestock systems (Soussana et al., 2007).

The Intergovernmental Panel on Climate Change (IPCC) pointed out that human actions are contributing to the increase of greenhouse gases (GHGs) in the atmosphere and have stepped up, especially extreme events with serious damage to humanity. Of all global anthropogenic CO_2 emissions, less than half accumulate in the atmosphere, where they contribute to global warming. The remainder is sequestered in oceans and terrestrial ecosystems such as forests, grasslands and peatlands (IPCC, 2007).

Considering concerns about climate changes, identification of soil, crop and livestock management to adapt and or mitigate GGE will be focused in new projects, for example, "AN Integration of Mitigation and Adaptation options for sustainable Livestock production under climate CHANGE – Animal Change" and "Role Of Biodiversity In climate change mitigation – ROBIN" in the Seventh framework program Food, Agriculture and Fisheries, Biotechnology (FP7). Further information and discussion about Brazilian researches related to livestock emissions of GHG are presented by Perondi et al (2011) and others in the site of "Global Research Alliance on Agricultural Greenhouse Gases (www.globalresearchalliance.org).

6. Conclusion

The soil water matric potential showed that drying front is longer in no-tillage system compared to conventional tillage and the CROPGRO-Soybean presented better performance to simulate phenological stages, growth variables and yield components under irrigated conditions than non-irrigated treatments, especially in conventional tillage. Crop yield results for no-tillage system presented low accuracy, mostly for water deficit, as shown by the test of Willmot, suggesting need for adjustment on model parameters to simulate soil water availability, especially for Brazilian agriculture, where no-tillage system area is increasing significantly.

7. Acknowledgement

The authors express their thanks to Brazilian Agricultural Research Corporation (Embrapa), the Federal University of Rio Grande do Sul (UFRGS), Institute Agronomic of

Parana (IAPAR), Foundation Research Agricultural of State Rio Grande do Sul (FEPAGRO) and the National Council for Scientific and Technological Development CNPq) for supporting scientific, financial and technological developments in this research. We would like also to thanks UFRGS/Agrometeorology Department to support scientific and friends for its support. The first author would like to thanks the colleagues Azeneth Schuler, Thomas Muello, Daiana Monteiro, Rodrigo Almeida, Leila Lisboa, Siglea Chaves and Salomão Rodrigues for having reviewed this paper.

8. References

Allen, D.J. & Ort, D.R. (2001). Impacts of chilling temperatures on photosynthesis in warm-climate plants. *Trends in Plant Science* Vol. 6, pp.36-42.

Bergamaschi, H., Guadagnin, M.R., Cardoso, L.S. & Silva, M.I.G. da. (2003). Clima da Estação Experimental da UFRGS (e Região de Abrangência). *Porto Alegre: UFRGS*. pp. 78.

Bergamaschi, H., Dalmago, A.G., Bergonci, J.I., Bianchi, C.A.M., Müller, A.G. & Comiran, F. (2004). Distribuição hídrica no período crítico do milho e produção de grãos. *Pesquisa Agropecuária Brasileira* Vol. 39, nº 9 (Set.), pp. 831-839.

Berlato, M.A. & Fontana, D.C. (1999). Variabilidade interanual da precipitação pluvial e rendimento da soja no Estado do Rio Grande do Sul. *Revista Brasileira de Agrometeorologia* Vol. 7, n.1, pp.119-125.

Basso, B., Gargiulo, O. Paustian, K., Robertson, G.P., Porter, C., Grace, P R. & Jones. J.W. (2011). Procedures for Initializing Soil Organic Carbon Pools in the DSSAT-CENTURY Model for Agricultural Systems. *Soil Science Society of America Journal* Vol. 75, Issue: pp. 1 - 69.

Buarque, S. C. (2006). *Construindo o Desenvolvimento Local Sustentável: metodologia de planejamento*. Ed. Garamond: São Paulo. Brasil. 177p.

Cargnelutti Filho, A., Matzenauer, R. & Trindade, J. K. da. (2004). Ajustes de funções de distribuição de probabilidade à radiação solar global no Estado do Rio Grande do Sul. *Pesquisa Agropecuária Brasileira* Vol.39, n.12, pp.1157-1166.

Dalmago, G.A. (2004). Dinâmica da água no solo em cultivos de milho sob plantio direto e preparo convencional. *Tese de Doutorado*. Porto Alegre: UFRGS, 2004. pp. 244.

Denardin, J.E., Kochhann, R.A., Flores, C.A., Ferreira, T.N. , Cassol, E.A., Mondrado, A. & Schwarezet, R.A. (2005). Manejo de enchurrada em Sistema Plantio Direto. Porto Alegre. pp. 88.

Dourado Neto, D., Nielsen, D. R., Hopmans, J. W. & Parlange, M. B. (2005). Soil water retention curve Vol. 1,0, Davis.

FAO (2006). Livestock's Long Shadow—Environmental Issues and Options. *Food and Agriculture Organization*, Rome, Italy.

FAO (2009). *How to feed the world in 2050.*

Faria, R. T. & Madramootoo, C. A., (1996). Simulation of soil moisture profiles for wheat in Brazil. *Agric. Water Manage*. 31, 35-49.

Faria, R. T. & Bowen, W. T. (2003). Evaluation of DSSAT soil-water balance module under cropped and bare soil conditions. *Brazilian Archives of Biology and Technology*, Curitiba Vol. 46, n. 4, pp.489-498.

Fehr, W.R. & Caviness, C.E. (1977). Stages of soybean development. *Ames: Iowa State University of Science and Technology*. pp. 11.

Global Research Alliance (2011). URL: http://www.globalresearchalliance.org/

Hoekstra, A.Y. & Chapagain, A.K. (2007). Water footprints of nations: Water use by people as a function of their consumption pattern. *Water Resources Management* Vol. 21, (Oct.), p. 35–48, 0920-4741.

Hoogenboom, G. (2000). Contribution of agrometeorology to the simulation of crop production and its applications. *Agricultural and Forest Meteorology* Vol. 103, p. 137-157.

Hoogenboom, G., Jones, J.W., Poter, C. H., Wilkens, P.W.; Boote, K.J., Batchelor, W. D.; Hunt, L. A. & Tsuji, G. Y. (2003). Decision Support System for Agrotechnology Transfer (Version 4.0) Vol. 1. *Honolulu: University of Hawaii*, pp.1-60.

International Consortium for Agricultural Systems Application. (2009). URL: http://www.icasa.net

IPCC (2007). Climate Change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *IPCC*, Cambridge University Press.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J. & Ritchie, J.T., (2003) The DSSAT cropping system model. *European Journal Agronomy* Vol. 18 pp. 235-265.

Lal R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science 304*, pp. 1623–1627.

Loague, K. & Green, R.E. (1991). Statistical and graphical methods for evaluating solute transport models: overview and application. *Journal of Contaminant Hydrology* Vol. 7, pp.51-73.

Major, D.J.; Johnson, D.R. & Luedders, V.D. (1975). Evaluation of eleven thermal unit methods for predicting soybean development. *Crop Science* Vol. 15, p.172-174.

Martin, T. N.; Storck, L. & Dourado Neto, D. (2007). Simulação estocástica da radiação fotossinteticamente ativa e da temperatura do ar por diferentes métodos. *Pesq. Agropecuária Brasileira [online]*Vol. 42, n.9, pp. 1211-1219. ISSN 0100-204X. URL: http://dx.doi.org/10.1590/S0100-204X2007000900001.

Martorano, L.G. (2007). Padrões de resposta da soja a condições hídricas do sistema solo-planta-atmosfera, observados no campo e simulados no sistema de suporte à decisão DSSAT. 2007. pp.151 p. *Tese (Doutorado em Fitotecnia/Agrometeorologia)*, Universidade Federal do Rio Grande do Sul, Porto Alegre.

Martorano, L. G., Faria, R. T., Bergamaschi, H. & Dalmago, G. A. (2007). Avaliação do desempenho do modelo CROPGRO-Soja para simular a umidade em Argissolo do Rio Grande do Sul. In: *Congresso Brasileiro de Agrometeorologia*, 15, 2007. Anais Aracaju: SBA, Brasil, pp. 4.

Martorano, L. G., Faria, R. T. de; Bergamaschi, H. & Dalmago, G. A. (2008 a). Evaluation of the COPGRO/DSSAT model performance for simulating plant growth and grain yield of soybeans, subjected to no-tillage and conventional systems in the subtropical southern Brazil. *Rivista di Agronomia: an international Journal of Agroecosystem Management*, vol. 3, nº 3 supp. (Jul./Sept.), pp. 795-796, 1125-4718

Martorano, L.G., Bergamaschi, H., Faria, R.T. de., Dalmago, G.A., Mielniczuk, J.Heckler, B. & Comiran, F. (2008 b). Simulações no CROPGRO/DSSAT do Carbono no Solo Cultivado com Soja sob Plantio Direto e Preparo Convencional, em Clima Subtropical do Sul do Brasil. *Anais da XVII Reunião de Manejo e Conservação de Solo e Água*, Rio de Janeiro, Brasil.

Martorano, L.G, Bergamaschi, H., Dalmago, G.A., Faria, R.T. de., Mielniczuk, J. & Comiran, F. (2009). Indicadores da condição hídrica do solo com soja em plantio direto e preparo convencional. *Revista Brasileira de Engenharia Ambiental* Vol. 13, nº 4 (Out.), p. 397-405, 1415-4366.

Matzenauer, R., Barni, N.A. & Maluf, J.R.T. (2003). Estimativa do consumo relativo de água para a cultura da soja no Estado do Rio Grande do Sul. *Ciência Rural* Vol. 33 (Nov./Dez.), nº. 6, pp. 1013-1019, 0103-8478.

Perondi, P. A. O., Pedroso, A. de F., Almeida, R. G. de., Furlan, S., Barioni, L.G., Berndt, A., Oliveira, P. A., Higarashi, M., Moraes, S., Martorano, L., Pereira, L.G.R., Visoli, M., Fasiabem, M. do C. R. & Fernandes, A. H. B. M. (2011). Emissão de gases nas atividades pecuárias. In: Simposio Internacional sobre gerenciamento de resíduos agropecuários e agroindustriais. *Foz do Iguaçu*, Paraná, Brasil. pp. 69-73.

Paz, J. O., Batchelor, W. D., Colvin, T. S., Logsdon, S. D., Kaspar, T. C. & Karlen, D. L. (1998). Analysis of water stress effects causing spatial yield variability in soybeans. *Transactions of the American Society of Agricultural Engineers* Vol. 41, n.5, pp. 1527-1534.

Ruiz-Nogueira, B., Boote, K.J.& Sal, F. (2001). Calibration and use of CROPGRO-Soybean model for improving soybean management under rainfed conditions. *Agricultural Systems* Vol. 68, Oxon, p. 151-163.

Soussana, J.F.& Luescher A. (2007). Temperate grasslands and global atmospheric change: a review. *Grass and Forage Science* Vol. 62, 127-134.

Tornquist, C. G., Giasson, E. ; Mielniczuk, J. ; Cerri, C. E. P. & Bernoux, M. (2009a). Soil Organic Carbon Stocks of Rio Grande do Sul, Brazil. *Soil Science Society of America Journal* Vol. 73, p. 975-982.

Tornquist, C. G.; Gassman, P.W.; Mielniczuk, J., Giasson, E. & Campbell,T. (2009b). Spatially explicit simulations of soil C dynamics in Southern Brazil: Integrating century and GIS with i_entury. *Geoderma (Amsterdam)* Vol. 150, p. 404-414.

Van Genuchten, M. T. (1980). A closed form equation form prediction the hydraulic conductivity of unsatured soils. *Soil Science Society of America Journal* Vol. 44: 892-898.

Willmott, C.J., Akleson, G.S., Davis, R.E., Feddema, J.J., Klink, K.M., Legates, D.R., Odonnell, J. & Rowe, C.M. (1985). Statistics for the evaluation and comparison of models. Journal of Geophysical Research Vol. 90, nº C5 (Sept. 1985), pp. 8995-9005, 0958-305X.

Edited by Manish Kumar

Food security emerged as an issue in the first decade of the 21st Century, questioning the sustainability of the human race, which is inevitably related directly to the agricultural water management that has multifaceted dimensions and requires interdisciplinary expertise in order to be dealt with. The purpose of this book is to bring together and integrate the subject matter that deals with the equity, profitability and irrigation water pricing; modelling, monitoring and assessment techniques; sustainable irrigation development and management, and strategies for irrigation water supply and conservation in a single text. The book is divided into four sections and is intended to be a comprehensive reference for students, professionals and researchers working on various aspects of agricultural water management. The book seeks its impact from the diverse nature of content revealing situations from different continents (Australia, USA, Asia, Europe and Africa). Various case studies have been discussed in the chapters to present a general scenario of the problem, perspective and challenges of irrigation water use.

Photo by meatbull / iStock

IntechOpen

ISBN 978-953-51-5233-0