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# Irrigation and Drainage
## Sustainable Strategies and Systems

*Edited by Muhammad Salik Javaid*

# IRRIGATION AND DRAINAGE - SUSTAINABLE STRATEGIES AND SYSTEMS

Edited by **Muhammad Salik Javaid**

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# Meet the editor

Dr. Muhammad Salik Javaid has been working on research, development, planning, execution, management and policy formulation assignments with the Corps of Engineers in Pakistan and abroad for over three decades. He has also worked as Chief Consulting Engineer with Engineer-in-Chief and Director General Planning for the Earthquake Reconstruction and Rehabilitation Authority in the wake of 2005 earthquake in Pakistan. Dr. Muhammad Salik Javaid is a graduate of Georgia Tech, Atlanta, USA where he undertook his Masters and Doctoral studies in the fields of Dam Overtopping and Ocean Bed Hydrodynamics. Presently he is the Head of Department of Civil Engineering at Abasyn University Islamabad Campus, Pakistan. Dr. Muhammad Salik Javaid has also conducted courses on 'water resource management' and 'river engineering' for civil engineering students at various campuses and universities.

# Contents

# Preface

The hallmark and acme of modern science and technology is in maintaining the delicate balance between the ecological nature trying for the “status quo” and the “change” demanded by engineering to meet the needs of present day lifestyle. The success lies not in delinking one from another but in finely balancing the causes and effects of each. “Irrigation and Drainage” put together, is an art of maintaining dynamic equilibrium between total water applied to the fields, its consumptive usage, groundwater recharge and discharge of the excess waters through surface and subsurface drainage. Irrigation and drainage; the two concepts have complimented each other since the inception of organized agriculture in human society. Quality and quantity of water made available for irrigation and drained effluent have always interested researchers, engineers, food growers and horticulturists in the communities all over the world. The concept of reusing the same water again and again after necessary conditioning has been adopted and is practiced to meet the quantity and quality deficiencies in irrigation waters.

The sustainability of any irrigation and drainage system in the face of many variants and constraints like availability of water as a resource, ecological balance, socio-cultural impacts, climate change effects, etc., has always remained a challenge for the users of irrigation waters and other stakeholders in all regions. The rise and fall of many civilizations may be directly or indirectly linked to the sustainability of their irrigation and drainage systems, hence their capacity to grow food for their hungry populace. The temporal and spatial distribution of natural waters and the effort to redistribute these as per the requirements and usages of stakeholders has gross effects on the sustainability of the systems. The natural uncertainties in the availability of water as a natural resource compound the planning and engineering challenges and thus affect the system sustainability.

The objective of providing irrigation and drainage is to assist nature in maintaining moisture in the root-zone soil within the range required for maximum agricultural production. Hence the irrigation and drainage may not be planned and designed as independent or isolated systems. Multivariate hydrological factors demand that irrigation and drainage systems be designed on a complete description of statistical properties and joint action of multiple factors like precipitation, climate, crop patterns and habitation patterns. Ancient civilizations showed great care when constructing irrigation and drainage systems, combining strategies of collecting rainwater, preventing flooding and conveying waste. A lot can be learnt from case histories and expertise from across the world.

The aim of this book is ‘to explore frontiers of knowledge in coining sustainable strategies and systems direly needed in managing the quality and quantity of water required for crop irrigation, surface and root zone drainage and flood management using available tools of research and development'.

For ease of comprehension and coherence in understanding, the material presented in this book has been divided into five chapters. First chapter is a case study carried out in Zimbabwe which deals with nature and role of water institutions for management of water resources. The second chapter deals with the waste water reuse for irrigation purposes. The third chapter deals with the Environmental aspects of wastewater irrigation and their agricultural services to nutrient-rich irrigated soils. The fourth chapter is a case study conducted in Pakistan that deals with the use of hydrological modeling techniques to enhance irrigation potential of a humid subtropical watershed. The fifth chapter deals with water balance of flooded rice in the tropics.

This book provides broad based understanding of the problems and their potentials for improvement of drainage and may be used by academicians, researchers and field professionals. 'Irrigation and Drainage Systems: Sustainable Strategies and Systems' could not have been written without the hard work of many eminent drainage professionals, hydrologists, water resources engineers, scholars and scientists the world over.

The pleasant and cool natured firmness and perseverance of Ms. Iva Simcic the Publishing Process Manager of InTech Open Access Publisher are appreciated for providing much needed guidance and support; and also constantly reminding me of the deadlines. The forbearance of my wife Sultana Salik and my children Humaira, Sumayyah and Hammaad during the period I was working on this book need be highlighted for providing me much needed time out of their stock. I am indebted to Muhammad Shahid for helping me as Assistant Editor. The Abasyn University is also thanked for providing me academic forum, technical, material and staff support to undertake this assignment.

Last but not least, the entire concept of InTech Open Access Publishing is lauded for its goal of global outreach and universal benefit to the human race.

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# Nature and Role of Water Institutions — Implications to Irrigation Water Management in Zimbabwe

K. Nhundu, A. Mushunje and F. Aghdasi

Additional information is available at the end of the chapter

## 1. Introduction

About 60% of the Southern African region is semi-arid or arid and suffers from periodic droughts [1]. This is compounded by the scarcity and poor management of irrigation water resources. The challenges of water scarcity for agricultural purposes present negative consequences on the general populace, more particularly in the rural areas. It is in these areas that the majority practise agriculture for their livelihoods with regards to food and incomes [2]. This has led to a decline in agricultural productivity. Declining agricultural productivity among smallholder farmers in Africa remains a major bottleneck in the development of the continent [3]. Agricultural production is dominated by rain-fed agriculture and irrigation systems are limited [4].

To this effect, management of agricultural water particularly in rain-fed systems remains imperative for improved farm level yields because the bulk of the food comes from rain-fed agriculture [2, 3]. Yet, evidence of the problems of water management is found throughout history [5]. Effective management of agricultural water requires continuous backup from policies and institutional frameworks [2, 3, 6]. Scholars have argued that institutions are very important to improve management problems [7, 8]. How to incorporate and sustain institutional innovations to ensure efficient use and management of irrigation water under diverse ecological, economic, social, and political constraints is an on-going debate on irrigation water resource development [9]. Efficient use and management of irrigation water require changes in institutions and new institutions [10].

In light of the above, a series of institutional arrangements have been presented as panaceas to improve water management: strong government agencies, user organizations, and water markets [5]. These approaches have conversely failed to achieve the required outcomes basically because of the variability of local situations and the difficulty associated with

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transferring institutions from one context to another were not considered [5]. Moreover, research has confirmed that lack of enabling policies and effective institutional frameworks are a major contributor towards poor management and utilisation of agricultural water in Sub-Saharan Africa [3, 6].

In light of the above, it is therefore important to understand that addressing the challenges that are associated with water management, there is need to consider the localised rules and norms and the authorities that therefore enforce them. This is over and above implementing appropriate and relevant technologies [11]. Therefore, there is need for instituting effective localised governance the effective application of community rules. Thus, this chapter seeks to investigate the nature and role of water management institutions to foster sustainable agricultural water resources management, particularly in Zimbabwe after the “fast” track land reform programme. The subsequent section discusses the major water reforms in Zimbabwe.

### 1.1. Redressing past water injustices in Zimbabwe

For close to two decades after independence water resource management continued to be governed by the 1976 Water Act. The need for water reform eventually emanated from the need to ‘redress colonial injustices in the water sector’ [12, 13, 14]. Increased continual privileged access to water by the white large-scale commercial agriculture for commercial interests called for an urgent need to reform the irrigation water sector in Zimbabwe. This was to be augmented by establishing a legal framework that would also guarantee an equal access to water for all Zimbabweans. Ensuring equitable access to water for rural people for productive uses contributes to the improvement of their livelihoods derived from the use of water. The water reforms that culminated in the 1998 Water Act began as a reaction to the 1991/92 drought, the worst in the country’s history [15]. Within this context, the 1976 Water Act was repealed by the 1998 Water Act and the Zimbabwe National Water Authority (ZINWA) Act. The Water Act of 1998 set the parameters of access and use of water as well as the establishment of Catchment and Sub-catchment areas based on hydrological boundaries.

### 1.2. Institutions: Nature and role

This chapter adopts a definition of institutions that encompasses both [16] and [17]. [17]’s definition implies that interactions with the environment are secondary to political, economic and social interactions whereas [16] notes that institutions are rules that can be used at multiple levels of analysis and such a definition does not seem to place priority of one factor over another. The major role of institutions in a society is to reduce uncertainty by establishing structure to human interaction [18].

The difference between formal and informal institutions is one of degree, not of kind, and in many cases some informal institutions gradually become part of their formal counterparts and some formal institutions take informal forms. Informal institutions are also considered extensions and local-level translations of formal institutions and are not purposively designed but evolve through spontaneous interaction, whereas formal institutions can be purposively designed [18, 19].

## 2. Effectiveness of institutions: A critical review

### 2.1. Formal institutions

A survey was conducted by [20] based on a technical and institutional evaluation of the Geray irrigation scheme in West Gojjam zone, Amhara region, Ethiopia. The results indicate that the scheme had been managed by the Water Users Association for four years, despite the fact that it had existed for 27 years. The overall performance of the Water Users Association in terms of managing the schemes was very poor. Water Users Association had no legal authority to enforce its by-laws.

In Harayana, India, [21] employed descriptive analysis to argue that the fact that the poorer households participated in water projects, this did not however, protect their interests. Community based organisations did not basically provide efficient irrigation services compared to the services provided by private organisations. Allocation of water, collection of irrigation service fees, and maintenance of irrigation infrastructure by contractors was more effective than by the community. In contrast, an almost similar study by [22] evaluated the performance of smallholder irrigation systems in Zimbabwe. The results showed that the farmer managed irrigation system performed better consistently than the government managed irrigation system.

In Sri Lanka, a study by [23] revealed that there were many problems in agency managed irrigation. Poor maintenance of irrigation facilities under public provision is a salient feature in many countries. There was heavy subsidisation of the irrigation management in Sri Lanka which had a poor record of cost recovery. Less than 50 percent of the maintenance costs have been collected from farmers at any time [24]. Similarly, as observed by [25], another major deficiency has been the pricing policies in irrigation. Pricing is not related to scarcity or the cost of delivery. Flat rate pricing means the marginal cost is zero which created inefficiency in water use.

### 2.2. Informal institutions

Several studies have acknowledged the fact that informal local level institutions can make a difference in water management [26, 27, 28, 29, 30, 31, 32]. However, the majority of practitioners and policy-makers advocate for the formal state-based water rights in water management issues, while avoiding consideration of the localised informal norms and rules. On the other hand, the researchers who were pro-informal arrangements seem not to put their support on advocating for adoption of the localised best practices, rather, they opt for amalgamation of the (new) formal and (existing) informal arrangements. However, acknowledging the local rules and norms as legitimate by the formal law, the way they are implemented will suppress the dynamics that are fundamental of local arrangements and thus negatively affects local rights, hence poor irrigation water management.

In efforts to fully understand the importance of informal rules, [33] examined gender issues and women's participation in irrigated agriculture in Carchi, Ecuador, using a combination of qualitative and quantitative methods of analyses. The findings showed that women's participation in water user associations is low, and culture plays a strong role in terms of their decision-making power. In addition, women tried to solve their irrigation-related problems through informal ways where they had more decision making power.

## 3. Conceptional framework: Institutional Decomposition Analysis (IDA)

In this study, and as employed by [34], the Institutional Decomposition Analysis (IDA) for measuring the effectiveness of water management institutions was decomposed into informal and formal institutions components. The later was further decomposed into three institutional components; *irrigation water law, irrigation water policy, and irrigation water administration*. The institutional facets were decomposed further to identify their institutional aspects (Figure 1). This framework provides a basis for a quantitative evaluation of both the institutional and the institution performance linkages.

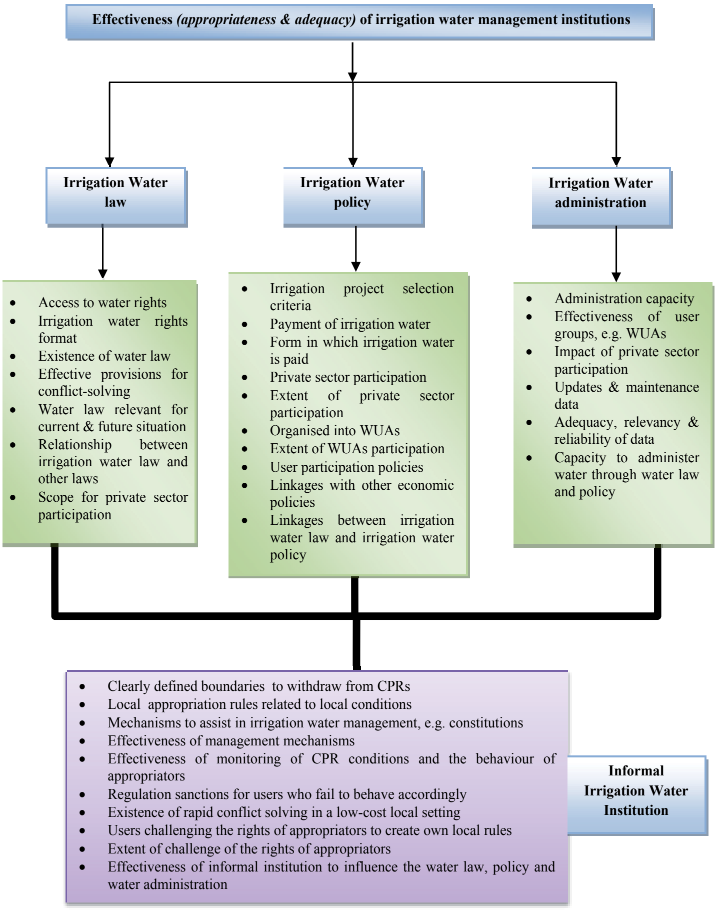

**Figure 1.** Conceptual framework

# 4. Methodology

## 4.1. Model specification

The dependent variable, effectiveness of the relevant formal and informal institution components, were assessed based on a ten-point Likert scale, 1 signifying an extremely non-effective institution and 10 signifying an extremely formal institution. A value of five implied an undecided or a neutral perception. The following set of equations describes the functional relationships of the formal irrigation institutions.

$$Effectiveness\ of\ IWMI\ = function\ (LOIWL,\ POIWP,\ AOIWA,\ INFWI)$$

The equation is based on the conceptual framework shown in figure 1

The definitions of the independent variables are listed in Figure 1 and Tables 1 - 4. The variables are grouped into categories of:

- Dummy variables. The value of 1 indicates the existence of a given institutional aspect; zero otherwise.
- Scale variables. A numerical value of 0 -10 is assigned for each category. A value of zero indicates the worst situation and 10 indicates an ideal situation. The intermediate values taken by the scale variables can be interpreted as the extent the actual situation deviates from either the worst or the ideal situation.

When these equations are estimated using Ordinary Least Squares (OLS), the sign and size of their coefficients provide insights into the relative role that various institutional aspects play in influencing the performance of the formal irrigation water institutions.

| Explanatory Variable | Acronym | Data type | Variable evaluation criteria |
|---|---|---|---|
| Access to water rights | LAWR | Dummy | 1 = yes; 0 = otherwise |
| Format of water rights | LFWR | Dummy | 0 = no rights;<br>1 = unclear/scattered rights;<br>2 = common state property;<br>3 = riparian system;<br>4 = correlative (proportional) sharing;<br>5 = licenses/permits |
| Awareness of the existence of irrigation water law | LEWL | Dummy | 1 = yes;<br>0 = otherwise |
| Provisions effective for conflict resolution mechanisms | LCRM | Scale | Captured in terms of judgemental perception; scale of 0 – 10 |

| Explanatory Variable | Acronym | Data type | Variable evaluation criteria |
|---|---|---|---|
| Water law relevant for irrigation water users under current and future situation | LRCF | Scale | Captured in terms of judgemental perception; scale of 0 - 10 |
| Relationship of water law with other laws to promote irrigation water management | LLOL | Scale | Captured in terms of judgemental perception; scale of 0 - 10 |
| Water law provisions to promote private sector participation | LPPS | Scale | Captured in terms of judgemental perception; scale of 0 – 10 |

**Table 1.** Irrigation water law component (LOIWL) with explanatory variable evaluation criteria

| Explanatory variable | Acronym | Data type | Variable evaluation criteria |
|---|---|---|---|
| Irrigation project selection criterion is economic-oriented | PPSC | Dummy | 1 = yes<br>0 = otherwise |
| Pay for use of irrigation water | PUIW | Dummy | 1 = yes<br>0 = otherwise |
| Form in which irrigation water if paid for | PFIP | Dummy | 0 = full subsidy (no payment)<br>1 = partial recovery<br>2 = full-cost recovery |
| Impact of the policy for promoting private sector participation | PGPP | Scale | Captured in terms of judgemental perception on a scale of 0 – 10 |
| Extensiveness of private sector participation in irrigation water management | PEPP | Scale | Captured in terms of judgemental perception; scale of 0 – 10 |
| Organised into Water Users Associations (WUAs) | PWUA | Dummy | 1 = yes<br>0 = otherwise |
| Extensiveness of WUAs' participation in irrigation water management | PEWA | Scale | Captured in terms of judgemental perception; scale of 0 – 10 |
| Impact of the policy for promoting users' participation | PIUP | Scale | Captured in terms of judgemental perception; scale of 0 – 10 |
| Extent of influence of other policies* on irrigation water policy | PEOP | Scale | Captured in terms of judgemental perception; scale of 0 - 10 |
| Extent of linkages between irrigation water law and irrigation water policy | PWPL | Scale | Captured in terms of judgemental perception; scale of 0 - 10 |

Some of these policies to be considered include: fiscal policies, economic policies, investment policies, etc

**Table 2.** Irrigation water policy component (POIMP) and independent variable evaluation criteria

| Explanatory variable | Acronym | Data type | Variable evaluation criteria |
|---|---|---|---|
| Capacity of the administration of irrigation water at scheme level | ACIW | Scale | Captured in terms of judgemental perception; scale of 0 – 10 |
| Effectiveness of user groups (WUAs) in administration of irrigation water | AEWA | Scale | Captured in terms of judgemental perception; scale of 0 – 10 |
| Private sector participation reduces administrative & management burden | APPA | Scale | Captured in terms of judgemental perception; scale of 0 – 10 |
| Mechanisms of collecting update and do maintenance at scheme level | AMUM | Dummy | 1 = yes<br>0 = otherwise |
| Adequacy, relevance, reliability of water data in irrigation water management at scheme level | AARR | Scale | Captured in terms of judgemental perception; scale of 0 – 10 |
| Capacity to administer irrigation water through use of the irrigation water law and policy | ACLP | Scale | Captured in terms of judgemental perception; scale of 0 – 10 |

**Table 3.** Irrigation water administration component (AOIWA) and variable evaluation criteria

| Explanatory variable | Acronym | Data type | Variable evaluation criteria |
|---|---|---|---|
| Clearly defined boundaries to withdraw irrigation water CPRs | ICPR | Dummy | 1 = existing;<br>0 = otherwise |
| Existing appropriation rules related to the local conditions | IARL | Dummy | 1 = existing;<br>0 = otherwise |
| Existing mechanisms, e.g. constitutions to assist in irrigation water management | IMSL | Dummy | 1 = existing;<br>0 = otherwise |
| Effectiveness of management mechanisms in water management | IEMM | Scale | Captured in terms of judgemental perception on a scale of 0 – 10 |
| Effectiveness of monitoring, conditions and the behaviour of appropriators | IEMA | Scale | Captured in terms of judgemental perception on a scale of 0 – 10 |
| Existence of regulation sanctions for users who fail to act accordingly | IERS | Dummy | 1 = existing;<br>0 = otherwise |
| Existence of rapid access to conflict solving in the low-cost, local setting | IECS | Dummy | 1 = existing;<br>0 = otherwise |
| Users challenging rights of appropriators to create own local-based institutions | ICRA | Dummy | Captured in terms of judgemental perception on a scale of 0 – 10 |
| Extent of challenge of the rights of appropriators to create own institutions | IECA | Scale | Captured in terms of judgemental perception on a scale of 0 – 10 |
| Effectiveness of informal institutions to influence law, policy and administration | IOEI | Scale | Captured in terms of judgemental perception on a scale of 0 – 10 |

**Table 4.** Informal irrigation water management institutions and variable evaluation criteria

### 4.2. Data collection

The research study was carried-out in Mashonaland East Province, Zimbabwe. Zimbabwe is divided into five broad Natural Regions (NR) in which the dominant natural factor conditioning agricultural production is climate; mainly rainfall.

Stratified sampling was done to categorise irrigation schemes into the three strata:

- A1 landless people;
- A2, commercial settlement schemes - small, medium, and large scale; and lastly
- Communal/resettled farmers.

From each stratum, random sampling was done to select the target irrigation schemes[1] in the province. The sample population for the study is depicted in Table 5. A total of 120 questionnaires were administered. The key instrument for data collection was a structured questionnaire which solicited both qualitative and quantitative data.

| Type of ownership | Number of schemes targeted |
|---|---|
| A1* irrigation schemes | 36 |
| A2 irrigation schemes | 43 |
| Communal/resettled irrigation schemes | 41 |
| **Total questionnaires** | **120** |

*Schemes under A1 category and collectively operated

**Table 5.** Stratification of the study population

## 5. Descriptive results

The descriptive results are summarized in Tables 6 – 9.

| Irrigation water law variables | Acronyms | Type of data | Mean values | Standard Deviation | Range | |
|---|---|---|---|---|---|---|
| | | | | | Min | Max |
| Access to water rights | LAWR | Dummy | 0.371 | 0.236 | 0 | 1 |
| Format of water rights | LFWR | Dummy | 1.340 | 0.117 | 0 | 5 |
| Existence of irrigation water law | LEWL | Dummy | 0.313 | 0.461 | 0 | 1 |

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[1] For a scheme to be selected for the study, it should have been functional for at least the past 5 years and at the time of the interview.

| **Irrigation water law variables** | **Acronyms** | **Type of data** | **Mean values** | **Standard Deviation** | **Range** | |
|---|---|---|---|---|---|---|
| | | | | | **Min** | **Max** |
| Provisions effective for solving conflicts among irrigation water users | LCRM | Scale | 3.641 | 3.314 | 0 | 10 |
| Water law relevant for irrigation water users under current and future situation | LRCF | Scale | 2.414 | 1.423 | 0 | 10 |
| Irrigation water law relationship with other laws to promote water management | LLOL | Scale | 4.341 | 2.532 | 0 | 10 |
| Water law provisions to promote private sector participation | LSPS | Scale | 5.266 | 2.160 | 0 | 10 |

Source: survey data

**Table 6.** Descriptive statistics: perceptional -based legal, institutional, and performance variables

| **Irrigation water law variables** | **Acronyms** | **Type of data** | **Mean values** | **Standard Deviation** | **Range** | |
|---|---|---|---|---|---|---|
| | | | | | **Min** | **Max** |
| Project selection criterion is economic-oriented | PPSC | Dummy | *0.214* | *0.428* | 0 | 1 |
| Pay for use of irrigation water | PUIW | Dummy | *0.384* | *0.413* | 0 | 1 |
| Form in which irrigation water is paid | PFIP | Dummy | *1.361* | *0.381* | 0 | 2 |
| Polices favourable for promoting private sector participation | PGPP | Scale | *3.148* | *3.861* | 0 | 10 |
| Extensiveness of private sector participation | PEPP | Scale | *3.266* | *2.184* | 0 | 10 |
| Organised into Water Users Association (WUA) | PWUA | Dummy | *0.318* | *0.426* | 0 | 1 |
| Extensiveness of WUAs participation | PEWA | Scale | *2.048* | *0.176* | 0 | 10 |

| Irrigation water law variables | Acronyms | Type of data | Mean values | Standard Deviation | Range | |
|---|---|---|---|---|---|---|
| | | | | | Min | Max |
| Policies favourable for users participation | PGUP | Scale | *3.648* | *2.481* | 0 | 10 |
| Effect of other polices like fiscal and economic policies | PEOP | Scale | *6.516* | *2.662* | 0 | 10 |
| Water policy links well with water law | PWPL | Scale | *2.018* | *0.748* | 0 | 10 |
| Source: survey data | | | | | | |

**Table 7.** Descriptive statistics: perceptional-based policy institutional and performance variables

| Irrigation water law variables | Acronyms | Type of data | Mean values | Standard Deviation | Range | |
|---|---|---|---|---|---|---|
| | | | | | Min | Max |
| Capacity of the administration of irrigation water at scheme level | ACIW | Scale | *6.162* | *2.242* | 0 | 10 |
| Effectiveness of user groups or WUAs in administration of irrigation water | AEWA | Scale | *4.733* | *2.149* | 0 | 10 |
| Private sector participation reduces burden on irrigation water administration and management | APPA | Scale | *5.147* | *1.240* | 0 | 10 |
| Mechanisms of collecting updates and do maintenance of irrigation water at scheme level | AMUM | Dummy | *0.234* | *0.108* | 0 | 1 |
| Adequacy, relevance and reliability of water data in irrigation water management at scheme level | AARR | Scale | *3.624* | *2.813* | 0 | 10 |
| Capacity to effectively administer irrigation water through use of the irrigation water law and policy | ACLP | Scale | *3.162* | *2.198* | 0 | 10 |
| Source: survey data (2012) | | | | | | |

**Table 8.** Perceptional-based administration institutional and performance variables

| Informal irrigation water institution variables | Acronyms | Type of data | Mean values | Standard Deviation | Range | |
|---|---|---|---|---|---|---|
| | | | | | Min | Max |
| Clearly defined boundaries to withdraw irrigation water from Common Pool Resources (CPRs) | ICPR | Dummy | *0.314* | *0.238* | 0 | 1 |
| Existing appropriation rules related to the local conditions | IARL | Dummy | *0.421* | *0.162* | 0 | 1 |
| Mechanisms, e.g. constitutions to assist in irrigation water management at scheme level | IMSL | Dummy | *0.204* | *0.191* | 0 | 1 |
| Effectiveness of management mechanisms in water management | IEMM | Scale | *4.184* | *3.005* | 0 | 10 |
| Effectiveness of monitoring conditions and the behaviour of appropriators at scheme level | IEMA | Scale | *3.881* | *2.748* | 0 | 10 |
| Existence of regulation sanctions at scheme level for users who fail to act accordingly | IERS | Dummy | *0.508* | *0.263* | 0 | 1 |
| Existence of rapid access to conflict solving in the low-cost, local setting | IECS | Dummy | *0.381* | *0.024* | 0 | 1 |
| Users challenging the rights of appropriators to create own local-based institutions suited to own local set-up | ICRA | Dummy | *0.215* | *0.138* | 0 | 1 |
| Extent of challenge of the rights of appropriators to create own institution based on diverse local set-ups | IECA | Scale | *3.587* | *2.782* | 0 | 10 |
| Effectiveness of informal institutions to influence the irrigation water law, policy and administration | IOEI | Scale | *4.499* | *1.033* | 0 | 10 |

Source: survey data (2012)

**Table 9.** Perceptional-based informal water institution and performance variables.

## 5.1. Formal institutions

### *5.1.1. Legal variables*

Water rights are mechanisms through which a user can access water for a particular use without jeopardising another user's right [35]. The descriptive statistics reveal that most users had little or no access to water rights (mean value = 0.37). During the colonial history of Zimbabwe, black indigenous farmers were disadvantaged because they had not applied for water rights [36] and when they applied for water rights, most of the water was committed to rights held by white farmers, which were issued in perpetuity and could not be revoked. Smallholder farmers were also disenfranchised because the legal systems introduced in the colonial and post-colonial states failed to acknowledge traditional water management practices [37]. In addition, [38] also report that the water rights of the indigenous population which predated the settler claims, were disregarded, thus leaving most farmers without water rights. Farmers' rights are found to be unclear/scattered or absent as shown by a mean value of 1.34, skewed towards the worst situation. Lack of clearly defined and well-enforced property rights significantly increase risks [39]. Unclear rights increase risks of farmers mismanaging water resources because they do not have a sense of ownership.

A mean value of 0.31 for the awareness of the existence of water law suggests that most users are not fully aware of the existence of the water law. The "Fast-Track Land Reform Programme" (FTLRP) brought in producers who may not have been aware of the existence of the water law. Human actors have bounded rationality (Simon, 1957) rather than perfect knowledge. Human actors lack complete knowledge to assess their decision alternatives due to their cognitive limitations, time and information constraints [40, 41].

There were weak provisions for conflict-solving within the water law (mean value = 3.64), suggesting that users may seek arbitration from legal courts. However, formal courts tend to nullify the rulings of informal arbitration [41]. This may imply perpetuation of conflict, eventually leading to poor irrigation water management.

The results reveal an irrelevant irrigation water law for current and future users (mean value = 2.41). This result can imply a lack of enforcement of the 1998 Water Act, despite the Act being regarded as technically sound, with a solid base for sustainable and efficient utilisation of water resources. Vital sections of the Act have not been fully enforced; hence, its founding principles are not supported. For example, the Water Fund has collected insufficient revenue to support statutory functions.

In the theory of economics of institutions and economic growth, [42] argued that institutions need continual adaptation in the face of changing environment of technology to promote economic growth, particularly in Zimbabwe where there has been an emergence of new irrigation farmers as a result of the land reform programmes. The results also reveal a weak relationship between irrigation water law and other economic laws (mean value = 4.34) such as environmental and energy laws, suggesting a lack of co-ordination of the laws, hence poor irrigation water management.

The water law provided for private sector participation in irrigation water resources management (mean value = 5.27). This can be explained by the fact that water reforms in Zimbabwe introduced radical changes regarding the participation and representation of users in the management of water. The 1998 Water Act provided a legal basis for the participation of previously excluded water users, namely communal, resettlement and small-scale commercial farmers. This inclusiveness has encouraged local level participation in water management at sub-catchment council levels.

### *5.1.2. Policy variables*

The descriptive statistics indicate that the project selection criterion was not economic-orientated (mean value = 0.21). In Zimbabwe, challenges exist in prioritisation of the development of water/irrigation projects according to well defined criteria [43] based on proper assessments of irrigation investments and projects, including their financial feasibility.

Generally, the purpose of paying for water use is to ensure sustainability of services, water conservation, and mitigation of damages [44]. However, the results depict non-commitment or non-payment of user fees (mean value = 0.38). Even the creation of the Water Fund embedded in the 1998 Water Act with the objectives of collecting levies, fees, government contributions and other support towards water service provision did not help as financial inflows have been minimal [45]. Similarly, new users are reluctant to pay for water use as water rights had not been paid previously. There is not a culture of paying for commercial use of water by water users [43]. Moreover, many farmers stopped paying for irrigation water after their farms were invaded during the FTLRP [44]. In addition, most farmers in Zimbabwe have refused to pay for water use, arguing that water is a natural resource that comes from "God", and even if they pay, the revenue is not re-invested back into their schemes. In response, many governments have moved away from imposing the full costs upon water users of irrigation for political reasons because farmers resist charges [45].

The findings reveal that payment of water was done on a partial recovery basis (mean = 1.36). This could emanate from political interference in pricing of water in Zimbabwe where politicians, in a bid to retain popularity, aim to keep the price of water as low as possible [43]. Even if users pay for irrigation water, a challenge lies on ensuring that at least part of the water revenue is re-invested in water management so as to improve and make the irrigation water policy an effective tool in irrigation water management [43].

As revealed by the results, the new irrigation policy did not fully provide for private sector participation (mean value = 3.15). After FTLRP, challenges existed in determining respective roles of the private and public sectors in irrigation [43]. The existing gap in roles played by the private and public sectors negatively affect irrigation water management objectives. Moreover, the results indicate poor participation of the private sector in water management issues (mean value = 3.27). As such, the irrigation water policy should provide for effective private sector participation on water management issues.

User groups, or Water Users Associations (WUAs), can play a crucial role in the management of irrigation water resources as most people feel a stronger sense of identity and belongingness. However, the results indicate that fewer farmers are organised into water user groups (mean value -0.32). This could be explained by the fact that it is difficult to identify and classify water user groups from which the representatives are chosen to constitute the sub-catchment. This is basically the challenge in spite of the 1998 Water Act provisions. For instance, the Water Act actually provided for the involvement of the farmers at communal level, however, the committees that are constituted at a local level hardly function and barely get recognition at catchment council meetings.

The current water policy lacks clear user participation provisions (mean value = 3.65). Regardless of the 1998 Water Act having the provisions for involvement and active representation of water users, the law has been overwhelmed by challenges. A good example is a case where new water users who lack financial resources to travel and attend sub-catchment council meetings, thus inhibiting them to attend the important meetings. In addition, the farmers indicate that other economic policies have an impact on the irrigation water policy (mean value = 6.52). Thus, water policy should clearly define how other policies are related with regards to water management objectives.

A weak relationship is revealed between water policy and water law (mean value = 2.02). After the FTLRP, no water law and/or policy reforms were put in place to address the needs of the new farmers introduced by the FTLRP. Irrigation water policy should link with the irrigation water law, so that the two work together in the management of irrigation water resources.

### *5.1.3. Administration variables*

The surveyed farmers indicate the existence of capacity to manage irrigation water resources management (mean value = 6.61), in the form of users' associations, irrigation scheme constitutions, etc. Farmers indicate that water users groups or WUAs are fairly effective in ensuring effective management of water resources (mean value = 4.73). However, [46] revealed that irrigation schemes were poorly managed due to a lack of well-established organisational and institutional conditions and WUAs were not well organised. In addition, as noted by [36], Irrigation Management Committees formed to improve coordination between irrigators and water management have not been able to take over the management of schemes because of state-applied technical measures.

As revealed by the surveyed farmers, private sector participation presents an opportunity to reduce the burden on irrigation water management (mean value = 5.15). Effective participation can be achieved if supported by administrative issues that accommodate water user groups. Water administration can ensure active participation of private sector in irrigation water resources by creating an active role for the private sector players and by reducing the burden on irrigation water management.

The survey reveals a lack of updates and maintenance mechanisms (mean value = 0.23). When irrigation systems dilapidate, it can lead to poor irrigation water management, for example, through water loss in case of burst pipes. Constant and regular monitoring of irrigation systems is needed. Irrigation schemes need mechanisms of collecting irrigation water updates and doing maintenance of irrigation water. However, where updates and maintenance schedules exist, farmers have indicated they are not adequate, relevant and/or reliable. Lastly a disparity between water administration issues and the water law and policy is revealed (mean value = 3.16). The disparities or lack of co-ordination among the formal institutions affect the effectiveness of water administration to manage water resources.

### 5.2. Informal institutions

The evolution of institutions and their performance implications are affected strongly by their path-dependency[2] nature. Because of their path-dependent characteristics, institutions are the 'carriers of history, ' reproducing themselves well beyond the time of their usefulness [47, 48]. Since informal institutions play an important role in the incremental way in which institutions evolve, they remain a major source of path dependence [18]. In addition to informal institutions, there are such self-reinforcing mechanisms as network externalities, learning effects, and the historically derived subjective modelling of issues. Since all these mechanisms reinforce the current course of the development path, reversing the course of that path becomes extremely difficult or costly [18]. This is also reiterated in the utility of social theory to address human problems [49], and is concerned with explaining how to improve economic performance, and hence welfare, by comprehending human incentives, preferences, perceptions, beliefs and learning [49]. Table 3 presents the perceptional-based informal irrigation water institutions and performance variables.

As revealed by the CPR studies, it is difficult to implant uniform institutional arrangements from locality to locality and situation to situation as the challenges that they face vary depending on physical and community conditions [50]. While effective institutional arrangements may deviate across settings, the CPR studies have identified common ideologies of long-enduring and self-governed CPR institutions. According to [7, 51], the first design principle associated with sustainable CPR governance institutions is the establishment of clearly delineated boundaries around the resource and resource users.

A mean value of 0.314 was revealed, suggesting clearly defined boundaries to withdraw irrigation water from CPRs clear boundaries not exist. This implies that any benefits the communities produce, by their efforts, will be gained by the other users who would not have contributed to the cause. [7]. However, [52] argues that there is a finite amount of water that must be shared in common over a variety of uses and over geographic areas, based on the fact that water falls in the form of rain, flows and evaporates with no regard to any boundary.

In addition, some CPR studies have identified general principles of long-enduring, self-governed CPR institutions by establishment of clearly delineated boundaries around the resource and resource users [7, 51]. It is therefore important that informal institutions be structured in a way that will ensure CPRs users coordinate their actions to solve supply and demand dilemmas [7, 50, 53, 54]. However, [7, 51, 55] highlights that CPRs exhibit varying degrees of two key characteristics, one of which is the difficulty in excluding users, as such; it will be difficult to exclude other users from accessing water resources, thus leading to free-riding problems or insufficient maintenance of water resources. Nonetheless, there should be effective conditions in place to ensure that water, as a CPR is effectively managed through the use of informal rules.

The informal local rules that are formulated are participatory, implying that the behaviour of all the users in the community or locality must customarily live in harmony with them. In

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[2] Path dependency means that history does matter: the direction and scope of institutional change cannot be divorced from its early course or past history.

addition, they are rules that govern human behaviour usually at no cost and they basically are enforced by the locals themselves [35]. In some cases, local rights could also be sensitive to the vulnerable, e.g. widows and the poor. Customary local practices and structures can also contain or help avoid conflict. A mean value of 0.421 was revealed, suggesting a lack of such- or fewer local rules. The FTLRP ushered in new water users who needed time to establish their own local rules, given that they take time to evolve. Violations of rules and water use may go unnoticed and unpunished. Existence of informal rules based on local condition means that if the informal codes are violated, punishment may be enforced [7]. On the other hand, however, [56] warns on viewing any particular institutional arrangement as a panacea for solving natural resources (especially CPRs) problems due to heterogeneity and complexity of problems facing different resources, hence, the need for local-based institutions. The local institutions at interplay within a local community regulate the users who have access to the CPRs, the resource units that the authorised participants can make use of at any given time, including who will monitor and administer the rules [55].

Regulation and governing mechanisms, e.g. constitutions at scheme level assist in the management of irrigation water resources. A mean value of 0.204 suggests a lack of these management mechanisms. A study by [57] revealed that often, there was no consensus on rules among farmers and monitoring and management mechanisms were absent. The new beneficiary farmers of the FTLRP were still not aware of the importance of informal management mechanisms. Thus, it is important to ensure the new farmers understand the importance of informal management mechanisms at scheme levels to promote effective irrigation water management. Where informal management mechanisms existed, their effectiveness was crucial to ensure efficient management of water resources. A mean value of 4.184 suggested that these mechanisms were not effective enough. The FTLRP beneficiaries did not have management mechanisms and had not organised themselves into user groups, where they would formulate some management mechanism.

Effectiveness of management mechanisms depends on factors like effectiveness of monitoring conditions, behaviour of appropriators, regulation sanctions, etc. A mean value of 3.881 suggests that monitoring conditions were not effective enough to assist in the management of water. Therefore, there is need to ensure the effective monitoring conditions and the behaviours of the appropriators to ensure all users behave accordingly and promote sustainable water management.

Existence of regulation sanctions can be an effective mechanism of irrigation water management as users who rebel, default and/or fail to behave accordingly can be possibly punished. A mean value of 0.508 was revealed, suggesting some existing regulation sanctions at some schemes. However, existence of regulation sanctions does not denote effective irrigation water management, unless they are effective. It is therefore important to ensure effective local regulation sanctions to ensure irrigation water management issues.

In addition to existence of regulation the sanctions, rapid access mechanisms to conflict solving without following long procedures or protocols can effective in the management of water resources. A mean value of 0.381 suggests non-existence of rapid conflict conflict-solving mechanisms. Lack of rapid conflict-solving mechanisms in a low-cost and local setting could have an adverse effect on irrigation water management. This encourages local users to by-pass traditional mechanisms in hope of achieving a winner-takes-all decision [35]. However, formal courts seem to have tendencies to overturn informal court decisions, in turn, may exacerbate conflict at local level rather than resolve it. In addition, these channels maybe costly and users may not be able to afford the expensive and lengthy procedures to solve conflicts, as such, may leave some of the conflicts unsolved and this negatively impacts on irrigation water management objectives.

According to the transaction cost theory, functioning of institutions depends on the costliness of enforcement [18]. Users need to create their own cheap set of rules that govern how they manage local water resources. Users will have confidence in their own rules and thus effectively implement them to ensure users behave accordingly. Development and creation of institutions or rules aid to creating more socially acceptable (and so economically acceptable) outcomes [58]. In addition, informal rules also differ from community to community, hence, the need of local, low-cost set of rules for water users. A mean value of 0.215 was revealed, suggesting that users were not in a position to create their own set of rules to govern water management. Institutions are not necessarily or even usually created to be socially efficient; rather, they are created to serve interests of those with bargaining power to create new rules [59]. Furthermore, creation of institutions that so structure the rules and their enforcement as to alter pay-offs induces the cooperative solutions.

Ability to challenge the rights of appropriators to create own institution based on local set-ups promotes effective water management, and depends on the extent of challenge. A mean value of 3.587 suggested the extent of challenging the appropriators' rights was low. Users were weak in challenging the rights of appropriators. As such, users could not create their own effective set of rapid, low cost and locally-based informal institutions. As such, users need to be empowered in creating their own set of rules.

As discussed in section 2.2, pro-informal arrangements scholars are not pushy to support the enforcement of informal institutions, rather opting for combining the new formal and existing informal arrangements in water management. As such, overall relationship and influence of the informal institutions and the formal irrigation institutions becomes important as the former guide the day-to-day management of water resources, yet, the latter tend to over-rule the informal rules. If the formal irrigation institutions are used to govern water management, farmers still have their own set of rules which determine their behaviour in a given context. A mean value of 4.499 suggested a lack of influence of the informal institutions on the formal institutions manage irrigation water management. Nonetheless, the formal institutions draw heavily from the informal institution [59]. Lack of coherence between the informal and formal institutions potentially leads to ineffective water resources management. In addition, users also originate from diverse social communities where a set of rules vary, as such, the formal rules structures should thus consider these differences to achieve irrigation water management objectives.

## 6. Empirical analysis results

This section presents the empirical results as shown in Table 10 -11.

| **Independent / explanatory variables** | **Acronyms** | **Range** | |
|---|---|---|---|
| | | **Coefficient** | ***t-ratio*** |
| Access to water rights | LAWR | *0.151*** | *2.177* |
| Format of water rights | LFWR | *0.083**** | *1.843* |
| Existence of irrigation water law | LEWL | *0.728** | *2.683* |
| Provisions effective for solving conflicts among irrigation water users | LCRM | *0.475**** | *1.617* |
| Water law relevant for users under current and future situation | LRCF | -0.069 | -1.189 |
| Water law relationship with other laws to promote water management | LLOL | 0.418 | *1.238* |
| Water law provisions to promote private sector participation | LSPS | *0.208** | *3.491* |
| ***Constant*** | | **1.641*** | 3.019 |
| **R$^2$** | | **0.681** | |
| **Chi-square ($\chi^2$)** | | **76.521** | |
| **Breusch-Pagan** | | **63.147** | |
| ***Significant at 1%** | ****Significant at 5%** | *****Significant at 10%** | |
| | **(a)** | | |
| **Independent / explanatory variables** | **Acronyms** | **Range** | |
| | | **Coefficient** | ***t-ratio*** |
| Project selection criterion is economic orientated | PPSC | *0.098**** | *1.653* |
| Pay for use of irrigation water | PUIW | *-0.079**** | *-1.683* |
| Form in which irrigation water is paid for | PFIP | 0.237 | 1.107 |
| Provisions for promoting private sector participation | PGPP | *0.091**** | *1.714* |
| Extensiveness of private sector participation in irrigation | PEPP | 0.087 | 0.839 |
| Organised into Water Users 'Associations (WUAs) | PWUA | *0.657** | *3.218* |
| Extensiveness of WUAs 'participation in irrigation water management | PEWA | *-0.181**** | *-1.650* |
| Provisions favourable for users' participation in irrigation | PGUP | *0.128*** | *2.052* |
| Effect of other policies like fiscal policies in water management | PEOP | *-0.121**** | *-1.645* |
| Water policy links well with water law | PWPL | *0.201** | *3.631* |

| **Independent / explanatory variables** | **Acronyms** | **Range** | |
|---|---|---|---|
| | | **Coefficient** | ***t-ratio*** |
| *Constant* | | 0.918** | 2.241 |
| **R²** | | **0.702** | |
| **Chi-square (χ²)** | | **78.023** | |
| **Breusch-Pagan** | | **64.818** | |
| _*Significant at 1%_ | _**Significant at 5%_ | _***Significant at 10%_ | |
| | **(b)** | | |
| **Independent / explanatory variables** | **Acronyms** | **Range** | |
| | | **Coefficient** | ***t-ratio*** |
| Capacity of the administration of irrigation water at scheme level | ACIW | *1.106** | *3.886* |
| Effectiveness of user groups / WUAs in irrigation water administration | AEWA | *-0.063**** | *-1.741* |
| Private sector participation reduces water management burden | APPA | -0.077 | -0.806 |
| Mechanisms of collecting updates and carry-out maintenance works | AMUM | 0.093 | 0.904 |
| Adequacy, relevant and reliability of water | AARR | 0.043 | 0.998 |
| Capacity to effectively administer irrigation water w.r.t law and policy | ACLP | -0.012 | -0.363 |
| *Constant* | | **1.248**** | 2.064 |
| **R²** | | **0.791** | |
| **Chi-square (χ²)** | | **73.947** | |
| **Breusch-Pagan** | | **67.184** | |
| _*Significant at 1%_ | _**Significant at 5%_ | _***Significant at 10%_ | |
| | **(c)** | | |

Source: survey data (2012)

**Table 10.** (a) Empirical results on the nature of institution–performance linkages: water law institutions; (b) Empirical results on the institution-performance linkages: water policy institutions; (c) Empirical results on the nature of institution–performance linkages: water administration institutions

| **Independent / explanatory variables** | **Acronyms** | **Range** | |
|---|---|---|---|
| | | **Coefficient** | ***t-ratio*** |
| Clearly defined boundaries to withdraw irrigation water from CPRs | ICPR | 0.167 | 0.388 |
| Existing appropriation rules related to the local conditions | IARL | *0.186*** | *2.238* |
| Existence of mechanisms, e.g. constitutions | IMSL | *0.783*** | *2.724* |

| Independent / explanatory variables | Acronyms | Range | |
|---|---|---|---|
| | | **Coefficient** | **_t-ratio_** |
| Effectiveness of management mechanisms in water management | IEMM | _0.319*_ | _4.543_ |
| Effectiveness of monitoring, conditions & behaviour of appropriators | IEMA | _-0.163***_ | _-1.656_ |
| Existence of regulation sanctions at scheme level | IERS | _0.689*_ | _4.891_ |
| Existence of rapid access to conflict-solving | IECS | **_1.418*_** | **_2.860_** |
| Users against rights of appropriators to create local-based institutions | ICRA | 0.278 | 1.019 |
| Effectiveness of users against rights of appropriators | IECA | 0.181 | 1.033 |
| Effectiveness of informal institutions on law, policy & administration | IOEI | 0.127 | 1.203 |
| **Constant** | | **1.613**** | **2.186** |
| **$R^2$** | | **0.817** | |
| **Chi-square ($\chi^2$)** | | **76.377** | |
| **Breusch-Pagan** | | **69.691** | |
| _*Significant at 1%_ | _**Significant at 5%_ | _***Significant at 10%_ | |

Source: survey data

**Table 11.** Empirical results: informal institution-performance linkages

## 6.1. Formal institutions

### *6.1.1. Legal variables*

A positive *regression coefficient of 0.151* at the 5% significance level suggests that access to irrigation water rights significantly strengthens the irrigation water law in the management of water resources. Private property [39, 60] Coase, 1960), just like water rights, is the most efficient system of land use. Similarly, North & Thomas (1977) support such an inference by arguing that property rights provide incentives to encourage development and cultivation.

A positive relationship between the water law and the format of water rights was revealed (*regression coefficient of 0.083)* at the 10% significance level. Unclear/scattered or lack of format rights, for example, may result in the water law failing to effectively manage irrigation water which can increase risks and transaction costs [39].

In his critique of instrumental rationality to further support the importance of institutions, [61] argued that the human mind fails to deliberately and analytically process all available information to choose an action that maximises utility. The study revealed that knowledge of the existence of the water law positively and significantly strengthens the effectiveness of the irrigation water law (*regression coefficient of 0.728)* at the 1% significance level. Lack of knowledge implies individuals have incomplete information and limited capacity to process information [59], thus it is necessary to educate farmers about the water law and its existence. Farmers may also choose an alternative that maximises their personal preferences and make decisions that lead to efficient outcomes [62].

The research findings reveal that if the water law provides for conflict resolution, it positively and significantly strengthens the effectiveness of the water law in the management of water resources. This is explained by a *regression coefficient of 0.475* at the 10% significance level. Effective conflict-solving provisions within the water law can ensure that certain protocols are followed without bias towards the parts concerned.

A positive relationship, (*regression coefficient of 0.208)* at the 1% significance level implies that provisions for private sector participation significantly strengthen the irrigation water law. Clear provisions that allow effective private sector participation in agricultural water management can lead to effective water management. Water law should provide for private sector participation to be an effective institution in managing agricultural water.

### *6.1.2. Policy variables*

The study findings revealed that the irrigation water policy is positively related to the criteria on how irrigation projects are selected (*regression coefficient of 0.098 at the 10% significance level)*. This suggests that project selection criterion significantly strengthens the effectiveness of the water policy to manage irrigation water resources. For example, if the irrigation water policy clearly defines selection of projects based on economic growth and development objectives, the water policy will become an efficient and effective water management institution.

The results of this study revealed a negative relationship between the effectiveness of the irrigation water policy and users paying for irrigation water, as shown by *regression coefficient of -0.079* at the 10% significance level. The implication is that if the irrigation water policy has clearly specified clauses on users pay principles, then it can significantly lead to effective irrigation water management. The negative relationship implies that failure of farmers to pay for water use negatively affects the effectiveness of the irrigation water policy to manage agricultural water, hence, can lead to poor irrigation water management.

There is a positive relationship between the effectiveness of the irrigation water policy and availability of provisions promoting private sector participation (*regression coefficient of 0.091)* at the 10% significance level. Unfavourable provisions may discourage private sector participation and in the long-run, may lead to ineffectiveness of the water law to manage water resources.

Organisation of farmers into Water User Associations (WUAs) positively and significantly strengthens the effectiveness of the irrigation water policy to manage irrigation water (*regression coefficient of* 0.657) at the 1% significance level. As such, favourable clauses within the irrigation water policy promoting and supporting users to organise themselves into users groups has the potential of sustaining efficient irrigation water use as WUAs may have the opportunity to enforce the use of restricted rules and regulations.

The results revealed a negative relationship *(regression coefficient of -0.181 at the 10% significance level)* between the effectiveness of the water policy and the extent to which WUAs/user groups participate in water management. The negative relationship revealed in this study implies that the WUAs have not been effective in irrigation water management. If the irrigation water policy promotes organisation of the farmers into user groups and/or WUAs, and allows for their extensive participation, it can lead to an effective and sustained irrigation water management. In addition, a positive *regression coefficient of 0.128* at the 5% significance level implies that policy provisions that favour farmers' participation leads to effective irrigation water management.

The results of this study revealed a negative and significant relationship between the irrigation water policy and its relationship with other economic policies *(regression coefficient of -0.121 at the 10% significance level)*. Lack of enabling policies and effective institutional frameworks are major contributors towards poor management and utilisation of irrigation water [3]. Moreover, the linkage between the irrigation water- policy and law revealed a positive and significant *regression coefficient of 0.201* at the 1% significance level. If the water law relates well to the water policy, it will lead to an effective irrigation water policy that will ensure efficient and sustained water resources management.

#### *6.1.3. Administration variables*

The results revealed a positive relationship between overall irrigation water administration and administration capacity at scheme level (*regression coefficient of 1.106)* at the 1% significance level). If administration capacity exists at irrigation schemes, it strengthens the overall irrigation water administration as a water management institution. Thus, capacitating farmers with administration roles, e.g. promoting organisation of farmers WUAs at scheme level can lead to effective irrigation water management.

The results revealed a negative relationship between overall irrigation water administration and the effectiveness of user groups or WUAs in the administration of irrigation water (*regression coefficient of -0.063* at the 10% significance level). Thus, administration conditions should promote effectiveness of users to manage water resources. WUAs, for example can formulate farm plans for the area, market local produce, distribute farm inputs, formulate rules for the maintenance of irrigation infrastructure, devise procedures for the distribution of water, and impose and collect irrigation fees (Samad, 2005). The observed negative relationship implies that currently, water users are not effective in the management of water resources.

### **6.2. Informal institutions**

According to [5], a series of institutional arrangements have been presented as panaceas to improve water management: strong government agencies, user organisations, and water markets. This is based on the fact that it is difficult to transplant institutions from one context to the other due to diversified and different local situations. As such, this paper also analysed how significant some of these arrangements are with regards to irrigation water management.

Informal irrigation water institution can be an effective water management tool if local appropriation rules related to local conditions exist. [63] argues that people will co-operate for their common good without provision of external (state) coercion. A positive *coefficient of 0.186 at* the 5% level was revealed between the effectiveness of informal irrigation institution and the existence of localised appropriation rules. An increase by one unit point in the explanatory variable increases the effectiveness of the informal institution in managing water resources. The significant relationship suggests that creating locally-based rules makes informal irrigation institution effective in water management. Institutions contain an element of predictability as institutionalised rules and norms hold a certain level of stability [64]. In addition, as institutions change, societies adjust themselves accordingly to adapt to the changes [30, 65].

Localised appropriation rules ensure that users behave according to defined rules and regulations, failure of which punishments will be effected upon the offenders as may be defined by the rules. However, these appropriation rules or conditions need to be strongly monitored to promote effective water management. This has been revealed by a *coefficient of -0.163* at the 10% significance level. A one unit point increase in the explanatory variable results in a decrease by 0.163 in the effectiveness of the informal institutions in managing irrigation water if the local rules are not monitored effectively. This implies that the informal institutions become effective water management institution if the created local rules are effectively monitored. Effective rules encourage members to co-operate towards a group strategy because they provide certainty about expected actions of others [63, 66].

Some management mechanism, e.g. constitutions, can be effective tools of implementing and monitoring localised appropriation rules. In light of this, the analysed empirical results revealed a positive *regression coefficient 0.783* at the 5% level. The relationship implies that a one-point increase in the explanatory variable leads to a 0.783 increase in the effectiveness of the informal institutions in managing irrigation water through effective constitutions. Management mechanisms ensure localised rules are effectively implemented. The relationship also suggests that the informal rules become effective water management tools if regulation mechanisms are existent and effective. Effectiveness of management mechanisms significantly strengthens the effectiveness of informal rules in managing water resources. This has been revealed by a *regression coefficient of 0.319* at the 1% significance level. A one unit increase in the effectiveness of management mechanisms increases the effectiveness of the informal institutions by 0.319. The results suggest that the more effective the management mechanism, the more effective the informal rules.

Effectiveness of management mechanisms can be explained by existence of regulation sanctions. Effectiveness in internal governance is needed for the effective application of community rules [11]. A significant relationship has been revealed between effectiveness of informal irrigation institutions and existence of regulation sanctions, as shown by a *coefficient of 0.689* at the 1% level. Existence of regulation sanctions increases the effectiveness of the informal institutions by 0.689 given a one unit point increase in the explanatory variable.

Existence of regulation sanctions ensures implementation of informal rules as an effective tool in managing water resources.

Existence of rapid access to conflict-solving in a low-cost and local setting significantly strengthens the effectiveness of formal rules to manage water resources. A *coefficient of 1.418* at the 1% significance level suggests that a one-point increase in the existence of rapid access to conflict-solving results in a 1.148 increase in the effectiveness of the informal water institutions. This suggests that farmers simply solve their conflicts at scheme level than attempting to follow the formal channels to courts, which may take long to solve such conflicts. However, formal courts tend to nullify the rulings of informal arbitration [35]. This may imply perpetuation of conflict, eventually leading to poor irrigation water management.

## 7. Conclusions

The main thrust of institutional change within the irrigation water sector is to enhance the capabilities and increase the readiness of policymakers to solve the current and future agricultural water resources challenges with regards to their development and management. Given this thrust, the major goals of institutional initiatives in the water sector include: treating water as an economic good where prices are attached to use of irrigation water; inculcating a payment culture; and promoting effective, sustainable, decentralized decision structures.

Institutional reform of the magnitude required to achieve these goals is a daunting challenge in Zimbabwe, particularly with the ineffective, irrelevant and poorly functioning irrigation water institutions. The issue of how to achieve irrigation water institutional change within the constraints and opportunities of political economy continue to remain elusive to both researchers and policymakers as most smallholder irrigation farmers still remain disadvantaged with regards to irrigation water resources development and management.

It is important to note that institutions typically change incrementally rather than in discontinuous fashion [11]. Even if some change is anticipated by a new policy or law, it is fairly common that the society adopts it slowly. The main reason for this incremental change is that there are many institutional elements which are interconnected, and a change gets cushioned by many other established institutional elements. Nonetheless, the important issue for policy makers is to ensure recommended polices are put on the table for consideration, especially in Zimbabwe where policy changes are imminent due to new users in the irrigation sector.

With regards to informal institutions, there were no clear boundaries to withdraw water resources from the CPRs, compounded by lack of local appropriation rules to regulate water management. Some management mechanisms did not exist at schemes, and where they existed, they not effective in managing water resources. Monitoring conditions and the behaviour of appropriators at scheme levels was not effective, owing to lack of effective management mechanisms and regulation sanctions. Rapid conflict-solving mechanisms were non-existent at schemes. Users had little capacity to challenge the rights of appropriators to create own local rules and the extent to which they challenge was not effective. The informal institutions were not effective enough to influence how the formal institutions manage water resources owing to the fact that the informal institutions are ignored and neglected, yet they guide the day-to-day water management activities. They are not regarded as instruments for effective irrigation water management, hence the lack of influence of the informal institutions on formal institutions. Lastly, the paper also noted the role and significance of the informal water management institutions in the effective management of water resources.

## 8. Policy recommendations

This research indicates that attempts to reform the water sector with the view to improve productive uses of water in rural areas, must confront the historical legacy of inequalities of access to land and water, which has continued under the FTLRP. One way of attaining improvement is to promote wide-scale participation of all stakeholders in the debate about the water reform over a long period of time. This will also entail seeking policy suggestions from all stakeholders, particularly the poor, on how water policy can be improved. Such an approach will break the stranglehold that government and donors have on the water policy-making process. In addition, issuance of water permits to water users will promote sustainable and efficient use of irrigation water resources. Water rights give farmers the sense of ownership and sense of belonging to water user groups which provides incentive to use water in a sustainable and efficient manner. The irrigation water law should provide clear provisions for the issuance of water rights.

In the Zimbabwean context, this study suggests that water reform must be linked, in innovative ways to the FTLRP, which aimed at providing access to productive land to rural people for livelihood improvement. It is the combined access to productive land and water, that water can be productively used to alleviate poverty and contribute to economic growth. Although access to fertile land is crucial to productive uses of water, new water users need access to a broad portfolio of other assets central to the productive use of water such as functioning irrigation technology and infrastructure. A new water policy should focus the development, provision and maintenance of relevant low-cost irrigation technology to communal farmers.

Water policy should provide greater local control of water charges. Revenue raised can be used to fund water development projects and maintain irrigation infrastructure within communal irrigation schemes. A policy that inculcates a culture of paying for commercial irrigation water and ensuring water revenue is re-invested in water resources development and management is needed along with the establishment of a water pricing structure that is consistent with cost and social efficiency.

There is a need to strengthen WUAs so these institutions can undertake the complex tasks of financial management and technical support to irrigation communities. These capacities are weak in most WUAs. Government can provide education to enhance local administrative, managerial, and financial capacities of participants. Water administration should encourage better coordination between public-public and public-private sectors. In areas where there is inadequate local revenue, government, private sector, NGOs and other development agencies can fund water development and the functioning of decentralised institutions of water management. There is need for information dissemination campaigns where the regulation of water users is undertaken.

Interventions to strengthen the capacity of the informal systems in managing water resources should be formulated and implemented effectively. This is because the formal institutions draw heavily from the informal institutions if they are to effectively work. Some local arrangements such as one-to-one conflict resolution mechanisms are more efficient, more cost-effective, longer-lasting and more widely accepted among local water users than most top-down state-driven institutions. When considering formal state-based institutions, water users should not think that they are a panacea to all water management challenges. In this regard, local informal water institutions should not be discarded as primitive and obsolete tools. Local water management arrangements need to be given time to evolve, with limited interference from external agencies, as they seek to address emerging water management imperatives especially in an environment that has been overwhelmed by new users in the irrigation sector.

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Chapter 2

# Wastewater Reuse for Irrigation — Practices, Safe Reuse and Perspectives

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Additional information is available at the end of the chapter

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## 1. Introduction

### 1.1. Wastewater for irrigation and its role in sanitation and human health

Human impact on water bodies has become relevant since water withdrawal, especially for agriculture, has resulted in overexploitation of rivers, lakes and aquifers. In most countries agriculture represents by far the largest use of water and worldwide, it represents about 70% of total withdrawal and 90% of water consumption [1]. To address this problem wastewater reuse has proven to be an alternative to reduce anthropogenic impacts [2]. In addition, raw wastewater reuse in agriculture is a valuable tool available to developing countries to control pollution and tackle the challenge of increasing food production in water scarce areas. The benefits of reusing water in agriculture are many and beyond doubt: it saves considerable amounts of first-use water that may be assigned to critical uses; it provides nutrients that may substitute chemical fertilizers, increasing soil fertility and crop yield, and reducing production costs; it makes it possible to expand agricultural land in arid areas; it is a relatively cheap disposal method for raw wastewater; and it may avoid pollution of surface water. In addition, it has been demonstrated that the health risks of reusing water in agriculture are minimal as long as its biological quality meets established criteria [3, 4].

However, it should be considered that there are potential negative impacts that may arise, such as soil salinization as well as soil and groundwater pollution with metals and organic compounds. In addition, the use of raw wastewater for crop production poses health risks due to its microbial content, especially bacteria, viruses and parasites, which produce a wide range of diseases since many of them may survive on the environment for long periods of time.

The main issue associated to wastewater reuse is related to public health and infection risks, either real (produces a disease) or potential (transmits the infection but the disease does not develop). Infection rates may be high, low or minimal, depending on the type of pathogen, the infective dose, and the susceptibility of the affected person (host). According to epidemiological studies over the last 20 years, when untreated wastewater is applied to land for crop production, there exist real infection risks caused by pathogens. To reduce such risks, control actions must be implemented, such as treating wastewater to comply with regulation limits; developing fast, cheap, easy, and efficient detection techniques; breaking the disease-infection cycle with medical treatment; and developing education campaigns for the population [4-6].

## 2. International and regional guidelines and country regulations for treated wastewater reuse in irrigation

Globally, wastewater reuse has become significant and this has encouraged many countries to develop local regulations to control water quality for reuse with the aim of reducing health and environmental risks. Due to different geographic, economic, and social characteristics, development of such regulations has been gradual and dissimilar among countries. Developed countries have worked on these regulations for several years and among them, the United States of America, and in particular the state of California, applied the first regulations on agricultural reuse in 1918 [7]. As a result, California has one of the most strict and complete regulatory frameworks. In addition, the United States Environmental Protection Agency (US EPA) has developed regulations and criteria for water reuse, which are used as a reference by many countries. Moreover, the creation of international organizations has led to the publication of general recommendations. The World Health Organization (WHO) published a series of four volumes that include information about agricultural irrigation and reuse in aquaculture [8]. At the same time, the Food and Agriculture Organization of the United Nations (FAO) has its own guidelines that are similar to those of the WHO [9]. WHO proposes limits for indicator bacteria (total or faecal coliforms) and helminth eggs when wastewater is reused for agriculture, considering that helminth eggs are highly resistant to treatment process and common in the environment.

In Europe, Mediterranean countries have detailed legislation about this topic, while countries with high water availability, such as Germany or the United Kingdom, do not regulate reuse as it is seldom practiced. Spain sets limits on faecal coliforms and nematodes based on their 1985 Water Law.

In the Americas, countries like Brazil, Costa Rica, Chile, and Mexico have made progress in developing regulations focused mainly on restricting water reuse based on microbial content, including indicator bacteria, helminth eggs and some metals, allowing organic matter and nutrients that are beneficial for agriculture to be used on land.

In Africa, despite the fact that several countries face a water crisis, many of them have lax or non-existent regulations and thus wastewater reuse is practiced uncontrolled. However, countries like Tunisia have detailed guidelines that include physicochemical and biological parameters, as well as heavy metals, an approach shared by some Mediterranean countries like Saudi Arabia, Israel, and Jordan [9].

In contrast, countries like Palestine, Libya, and Afghanistan, which have low water availability, have not been able to develop their own standards due to political conflicts and generally use either FAO or WHO guidelines. Finally, Indian regulation is outdated (1974) and limits just a few parameters, even though it has the world's second largest population.

Usually, most regulations for reuse in irrigation establish limits on one or more of the following parameters: indicator bacteria (total or faecal coliforms), helminth eggs (intestinal worms), nematodes (a subgroup of helminthes), organic matter (as biochemical oxygen demand, BOD), dissolved and suspended solids, and heavy metals.

## 3. Successful cases of wastewater reuse for irrigation

Demographic growth and economic development of emerging American countries has promoted the implementation of several agricultural reuse projects, some of which are summarized below.

In Mendoza, Argentina, an area known as Campo Espejo used to be irrigated with raw wastewater (2,000 ha) but currently, 129,600 $m^3$/d originating from stabilization ponds are supplied for the irrigation of 1900 ha [10].

Chile has several successful reuse projects such as the Maipo and Maipocho regions where 130,000 ha are irrigated [11]; Antofagasta where about 20,000 $m^3$/d of treated water are produced and 65 ha are irrigated; and Santiago de Chile with 110,000 ha that use reclaimed water mixed with first-use water [10].

In Mexico, the central and northern part of the country, where 80% of the population live, is considered arid or semi-arid, and cities like Ciudad Juarez irrigate 26,000 ha with approximately 400,000 $m^3$/d of reclaimed water. Additionally, the Mezquital Valley, covering more than 90,000 ha, is one of the largest areas in the world where agricultural reuse is practiced [12] and where a large wastewater treatment plant (35 $m^3$/s) is under construction to improve water quality for irrigation.

In South America, Peru encompasses a number of different biomes that range from Amazon rainforest (more than 50% of the country) to the west coast, an area with low precipitation where most of the population lives, and where small irrigation projects like San Agustin (535 ha) and Tacna (738 ha), have been developed [10].

## 4. Case study: Tula Valley, Mexico

The Tula Valley (also known as Mezquital Valley) is one of the largest areas irrigated with untreated wastewater in the world. The fact that it has been receiving wastewater since the late XIX century, and specifically for irrigation since the early XX century, makes this a unique site with regard to wastewater reuse. A large number of studies have described several processes and phenomena that emerge out of this practice, including incidental aquifer recharge, increase in crop yield, and treatment of the wastewater by the soil (in the same way as a soil-aquifer treatment system, SAT).

Concurrently, other studies have found an increase in health risks after using untreated wastewater in agriculture due to the presence of pathogens, heavy metals, and organic compounds in soil and even in groundwater. This section summarizes the history and current situation of the Tula Valley to share some lessons learned for more than 100 years of water reuse.

### 4.1. Metropolitan Area of the Valley of Mexico and Tula Valley

The Metropolitan Area of the Valley of Mexico (MAVM) has a population of 21.2 million and covers the Federal District (Mexico City) and 60 surrounding Municipalities (59 located in the State of Mexico and 1 corresponding to the State of Hidalgo). Water use is estimated to be 82 $m^3/s$ which includes 91% first use water and 9% reclaimed water. The rate of wastewater generation (including collected precipitation) ranges from 52 to 300 $m^3/s$ depending on the season, and it is conveyed to the Tula Valley. The reason for this practice is that Mexico City is located in an endorheic (closed) basin from which wastewater and excess precipitation needs to be transported to avoid flooding. On average, 60 $m^3/s$ are sent by gravity or pumping to the Tula Valley via four artificial exits (Figure 1): the Tajo de Nochistongo (deep cutting through Nochistongo Hill; 1607-1789); the Tequixquiac Tunnel (1900); the New Tequixquiac Tunnel (1955) and the Central Emitter (1975). Currently, a fifth exit (East Emitter) with a capacity of 150 $m^3/s$ is being constructed along 62 km and will be operating by 2016.

The Tula Valley is located 100 km north of Mexico City, with an elevation that ranges from 1,700 mamsl in the north, to 2,100 mamsl in the south. The climate is semiarid with an annual precipitation of 550 mm (national average is 790 mm) mainly between May and October [10] which contrasts with evapotranspiration that reaches 1,524 mm/y.

Originally, soils were low in organic matter and nutrients, and with such low precipitation, productivity was also low. By the end of the XIX Century, the Tula Valley started receiving raw wastewater from the MAVM. The first documented use of wastewater for irrigation in areas closed to the Salado River was reported around 1896. However, officially, reuse initiated in 1889 when wastewater was used to produce energy at the Juandhó and La Cañada hydro-electric plants [13], and in 1912 for irrigation [14].

As wastewater generation gradually increased, the irrigated area grew from 10,000 ha in 1920, to 80,888 ha today (Figure 2). This means that about 1,350 $Mm^3/y$ are transported a distance of 98 km to the Tula Valley. Once in the Valley, wastewater is distributed through a complex hydraulic system that includes six storage dams (combined capacity: 347 $Mm^3$), 323 km of main distribution canals, 264 km of lateral distribution canals, and 101 km of agricultural drains. Year-round availability of wastewater, as well as its organic matter and nutrient content which

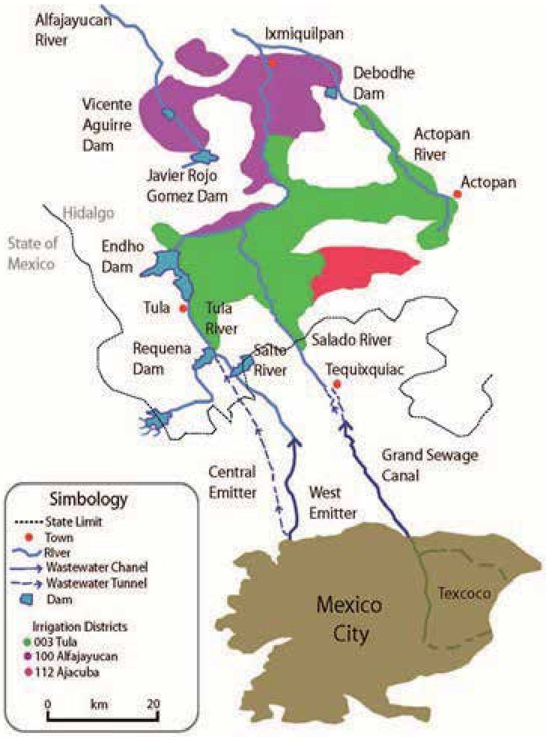

**Figure 1.** Wastewater transport and use in the Tula Valley.

act as fertilizers, allowed the development of three important Irrigation Districts (ID 003, 100, and 112) that today cover more than 85 thousand hectares [15].

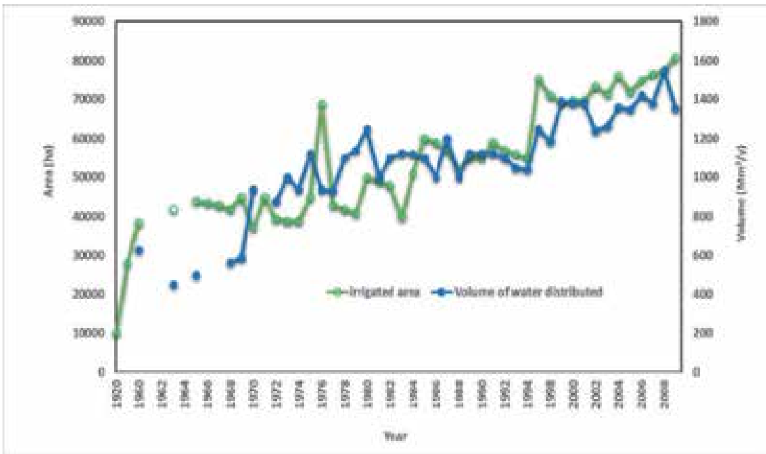

**Figure 2.** Growth of area irrigated and volume of water distributed since 1920 (adapted from [16], with data from [15]).

### 4.2. Water reuse in the Tula Valley

The gradual growth of the productive area in the Tula Valley allowed the differentiation of regions with various irrigation ages (Figure 3). Irrigation was first performed in the south-central area of the Valley [14]. Subsequently, when the City expanded and had to dispose of a larger amount of combined wastewater, the irrigation area grew towards the north and the east following the Tula River. Subsequent expansions of the Irrigation Districts carried wastewater to the east and southeast (ID 100), where reuse had started by 1970 [16].

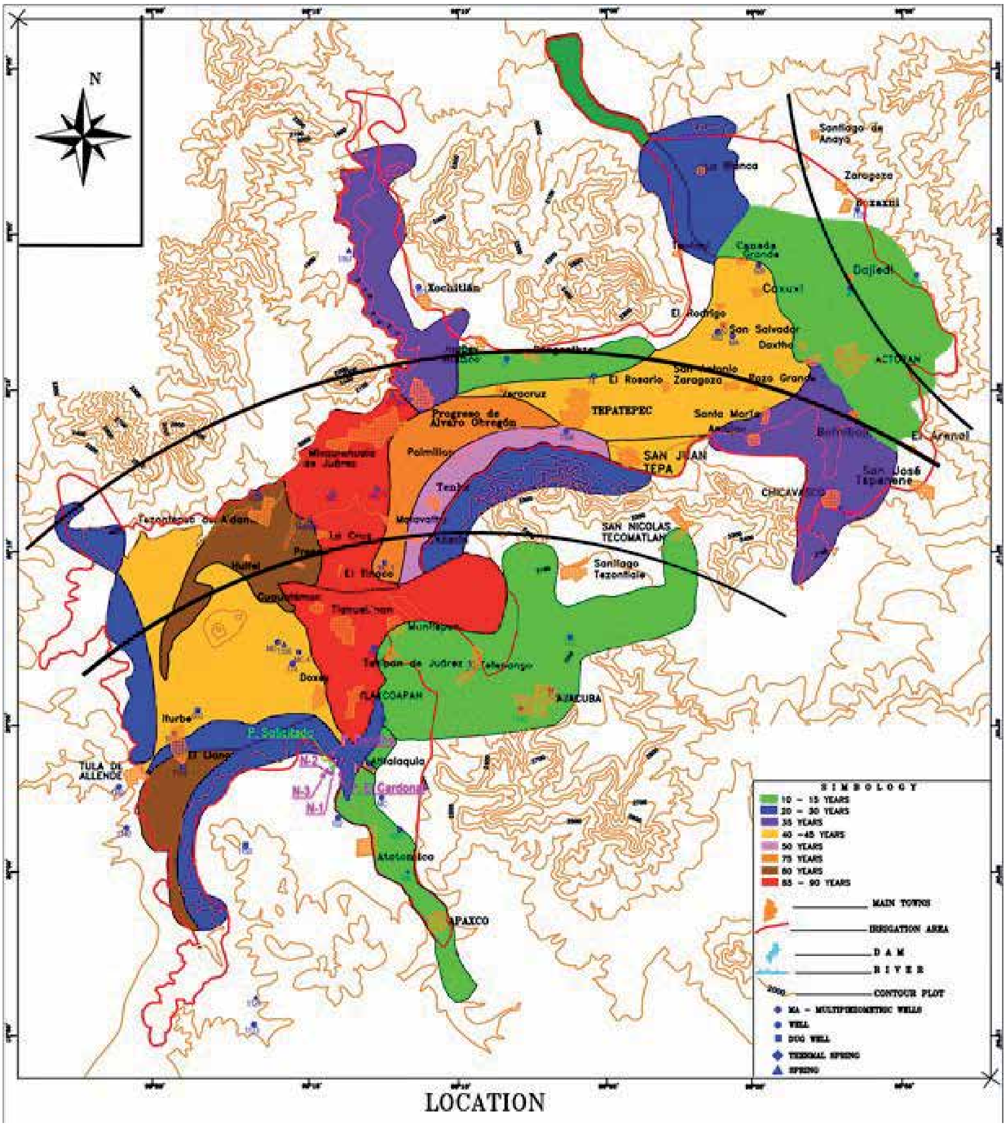

**Figure 3.** Areas under irrigation for different lengths of time (adapted from [16]).

Recently, wastewater was taken to the far east of the Valley, close to the Ajacuba Municipality (ID 112). As a result, the quality of irrigation water exhibits spatial and temporal variations. For example, in the southern part of the Valley, approximately 10,000 ha are irrigated with raw wastewater, while about 35,000 ha in the central and eastern regions receive diluted wastewater (80% wastewater and 20% river water/precipitation from the Taxhimay and Requena dams) with a different composition.

On the other hand, 25,000 ha located in the far west region of the Valley are irrigated with partially treated wastewater after being stored in the Endho dam which acts as a large settling tank with a hydraulic retention time of up to three months. Finally, the northern areas use well water or return flows and are mainly utilized for growing vegetables and fruits [17].

### 4.3. Water quality

#### *4.3.1. Microbiological indicators*

The potential risk of bacterial, viral and parasitic diseases that can be transmitted through the human-water-soil-crop-human cycle constitutes the greatest problem associated with the use of wastewater in agriculture, for human consumption or for other uses. Thus the study of their removal is especially relevant in developing countries where they represent the higher risk of disease.

The presence of microorganisms can be a serious cause for concern. For example bacteriophages (viruses) are resistant in the environment, have been shown to have the capacity to penetrate and reach confined aquifers, and have low infective doses [7]. Cysts of *Giardia lamblia* can survive and remain active for months or even years, are resistant to chlorination, have a low infective dose and can have serious consequences for vulnerable individuals [18]. Helminth eggs also survive for long periods of time in the environment, have a low infective dose and their incidence in Mexico is very high [19]. Faecal coliforms are a universally accepted indicator of faecal contamination and have been found to migrate through soil [20].

Wastewater from the MAVM reaches the distribution system at the Tula Valley without any treatment and thus it contains a high concentration of faecal coliforms (between $10^5$ to $10^8$ colony forming units, CFU/100 mL), *Streptococcus faecalis* ($10^2$-$10^6$ CFU/100 mL), *Clostridium perfringens* ($10^3$ to $10^6$ CFU/100 mL), somatic bacteriophages ($10^2$ to $10^6$ plaque forming units, PFU/mL), *Giardia* spp. (450 to 10,000 cysts/L), and helminth eggs (1.8 to 23 helminth eggs/L) (Table 1). This quality has shown little temporal variation but the concentrations registered pose a significant health risk in areas under irrigation, according to WHO [4].

To evaluate temporal and spatial variability along the Valley, samples from different regions have been taken for microbial analyses during the wet and dry seasons. Zone 1 (south) uses raw wastewater for irrigation and has shown higher concentrations of biological indicators than Zones 2 or 3 which correspond to areas with some sedimentation and dilution (rainfall and groundwater). This variability was due to the nature of the wastewater but there was a large decrease in the *Giardia* spp. content in all zones during the dry season. Helminth eggs showed little variability within the three zones and there was no obvious difference between the wet and dry seasons. However, both *Giardia* spp. and helminth eggs were relatively high in zone 3 at the farther reaches of the distribution system, which suggests a possible direct contribution from local discharges, since population in this zone is relatively high (Figure 4). The concentrations of microorganisms reported are similar to those previously described for untreated wastewater in Mexico [19] and are similar to untreated wastewater from other countries [21, 22], but much greater than concentrations seen in effluents of treatment plants [19].

| Parameter | Concentration | Description |
|---|---|---|
| Faecal Coliforms, Log(CFU/100 mL) | 6.53 ± 0.58 (5.15-7.84) | Traditional indicator of faecal contamination; may indicate the presence of pathogens; behaves similarly to other bacteria under different environmental conditions. |
| *Streptococcus faecalis*, Log(CFU/100 mL) | 5.15 ± 1.0 (2.04-6.20) | Intestinal bacteria found in the faeces of all warm-blooded mammals; useful for indicating the quality of water for recreational use and also for reuse. |
| *Clostridium perfringens* spores, Log(CFU/100 mL) | 4.70 ± 0.81 (3.00-5.97) | Anaerobic bacteria that have been recently used as an indicator of faecal contamination; they form a resistant spore commonly found in faeces which is more resistant to disinfection and adverse environmental conditions that many pathogens; the presence of vegetative cells indicates recent contamination while spores imply prior contamination. |
| Somatic bacteriophages, Log (PFU/mL) | 3.63 ± 0.77 (2.41-6.41) | Viruses that infect bacteria; used as indicators based on ease of detection by analytical laboratories; the coliphage group has been the best model for enteroviruses, given their similar physical structure and their greater resistance to treatment processes (such as chlorination); it is always present and relatively abundant in wastewater; easily detected over a short time period (24 h). |
| *Giardia* spp., Cysts/L | 2,231 ± 231 (450-10,000) | Pathogenic protozoa; single celled organisms that develop in two ways: as trophozoites, and as cysts; Infection results from the consumption of a mature cyst that is resistant to the gastric juices; the trophozoites can become cysts again in a process that is apparently aided by unideal luminal conditions, and they are then expelled in the faeces of persons with symptoms of the illness or with no apparent symptoms. Cysts can survive and remain active for weeks, months or even for periods of up to 7 years; capable of forming cysts (resistant structures) under adverse conditions, this organism represents a serious health risk. |
| Helminth eggs, eggs/L | 13.1±6.2 (1.8-23.0) | Group of parasitic and free-living worms of various sizes and shapes; they cause mechanical deterioration, tissue damage, toxic effects, and blood loss; intestinal parasites cause anaemic malnutrition and/or delayed growth; they present high resistance to chemical and physical conditions and thus are considered the most resistant form of parasites; they have the ability to survive long periods of time in biosolids and soil (up to 6 years after their initial application). |

**Table 1.** Microbiological quality of raw wastewater and characteristics of selected indicators (values in parenthesis indicate range of concentration).

Although it was expected that concentrations of microorganisms would be lower in the wet season due to rainfall dilution, this happens intermittently as the wet season is characterized by irregular intense storms. An additional issue is that the wastewater is mixed with stored rainwater and wastewater depending on the amount of water required by farmers and thus its quality exhibits some variability.

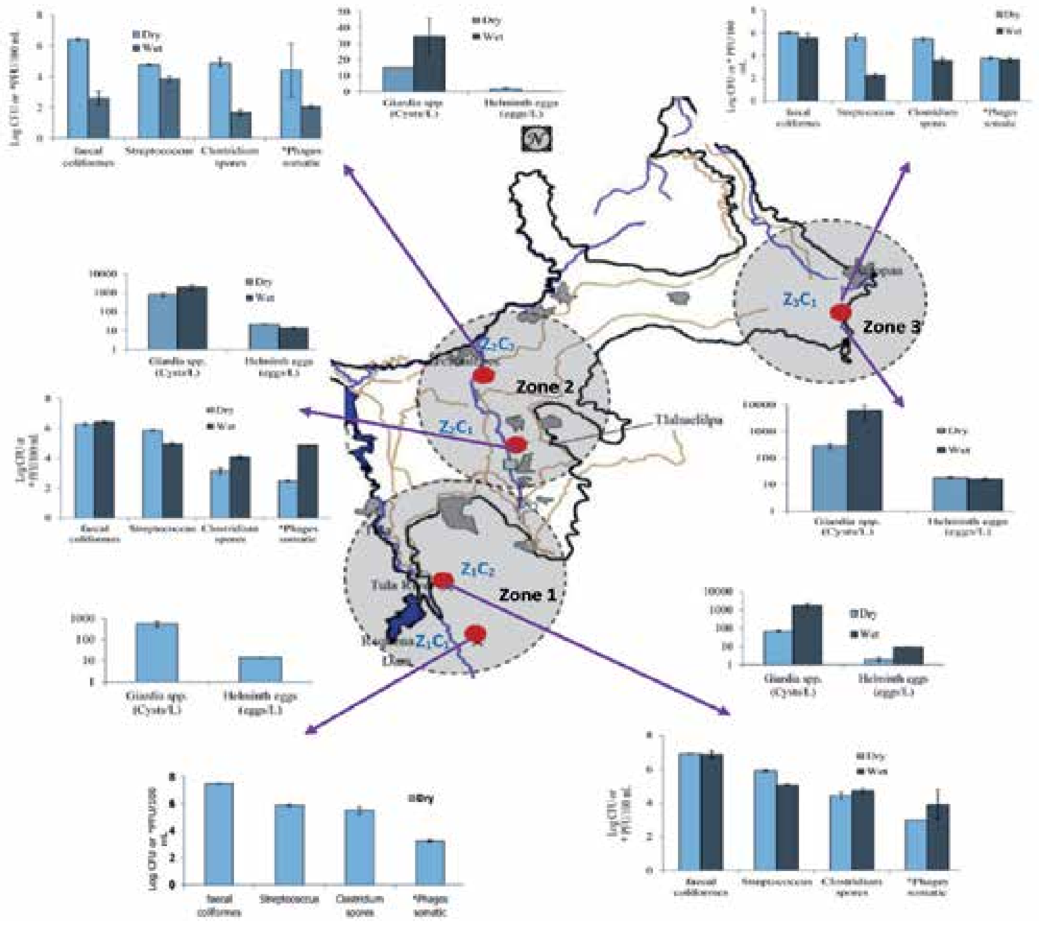

**Figure 4.** Concentration of selected microorganisms in different zones of the Tula Valley (Adapted from [10] and [23])

### 4.3.2. *Emerging pollutants*

Emerging pollutants are defined as those unregulated pollutants that may be controlled by future regulations depending on their potential effects on health and ecosystems [24]. Advances in analytical techniques for their detection and an increased understanding of their effects on public health and the environment, has increased the need to establish discharge limits worldwide. During the last two decades, the study of emerging pollutants (such as pharmaceuticals, personal care products, and endocrine disruptors included as additives of gasoline, plastics, or detergents) in the environment has gained scientific attention. Many of these studies have been performed in aquatic ecosystems in the United States of America and Europe [24]. However, for most of the emerging pollutants there are still insufficient data to indicate their risk and ecotoxicity and thus their effects on human health or aquatic organisms remains unknown. Many of these compounds reach the environment through wastewater and they may be removed in wastewater facilities, however, some of them remain in treated effluents and enter the environment, eventually reaching groundwater [25, 26].

Initial reports on pharmaceuticals in wastewater were published in the United States in the 1970's [27], however, even though their presence has been related to fish toxicity, little attention has been given to them [28, 29]. Considering that developed countries have detected emerging pollutants in water and wastewater, even after treatment, their presence in wastewater from the Metropolitan Area of the Valley of Mexico was clearly expected. Furthermore, the fact that many prescription drugs in developed countries are considered over-the-counter medications in Mexico, there is a higher probability of finding their active ingredients in wastewater.

On the other hand, agricultural irrigation favors the transport of pollutants, such as pesticides, from soil to groundwater. Several factors influence their incidence in groundwater, including soil permeability, the depth of the unsaturated zone, geological composition, as well as the solubility, partition ($K_{o/w}$), and dissociation (pKa) values of the pollutant. These conditions may promote their adsorption to soil particles or their leaching to groundwater. It has been reported that wastewater irrigation, treated or untreated, increases the concentration of pesticides in groundwater [30].

As mentioned previously, the presence of emerging pollutants was expected in wastewater from the MAVM, and thus at the Tula Valley, and was confirmed by different studies. Some of them [31] analyzed wastewater samples and found a variety of compounds with the exception of clofibric acid. Concentrations found were similar to those reported for wastewater samples taken at treatment plants (Table 2), but higher than those reported for their effluents [32, 33]. The concentrations of naproxen, a widely use pharmaceutical in Mexico, as well as salicylic acid were higher than those reported in other countries, while ibuprofen, diclofenac, are variable in comparison. Other compounds like 4-nonylphenol and diethylhexyl phthalate were the predominant endocrine disruptors in wastewater. Levels of Triclosan, bisphenol-A, butylbencylphtalate, estrone, and 17β-estradiol were similar to those reported elsewhere [33].

It was observed that dilution occurred during the rainy season when reported concentrations of endocrine disruptors were about half of those during the dry season. It should be noted that wastewater at the Tula Valley includes precipitation from the MAVM. Nonetheless, acid pharmaceuticals remain similar in both seasons which may suggest another phenomenon.

Siemens *et al*. [39] concluded that six acid and five basic pharmaceuticals measured in raw wastewater, irrigation water, and spring water, were reduced in concentration along the wastewater distribution canals. However, the authors suggest that acid compounds may permeate clay soils and exhibit poor removal compared to basic or neutral chemicals. Nevertheless, none of the reported compounds were found in spring water.

| Compound | Germany[a,c] ng/L | Spain[d] ng/L | Finland[e] ng/L | Brazil[b,c] ng/L | Mexico[f] ng/L |
|---|---|---|---|---|---|
| Ibuprofen | 3,400 | - | 13,100 | 3,300 | 2,500 |
| Diclofenac | 2,000 | 2,600–5,700 | - | 800 | 1,607 |
| Ketoprofen | 300 | - | 2,000 | 500 | 447 |
| Salicylic acid | 340-5,400 | - | - | - | 29,867 |
| Naproxen | 440 | 1,800–4,600 | 4,900 | 600 | 13,620 |

[a][34, 35] [b] [36]; [c][25]; [d][37]; [e][38]; [f][31].

**Table 2.** Concentration of pharmaceutical compounds in wastewater.

### 4.4. Natural attenuation of basic parameters, organic pollutants and pathogens in soil

In the Tula Valley, known as the largest case of indirect wastewater reuse for human consumption in the world, natural soil aquifer treatment (SAT) has been taken place for more than 100 years, recharging the aquifer and acting as a barrier to prevent contaminants from entering it. The local aquifer is being recharged at a rate of 25 $m^3/s$ due to the infiltration of untreated wastewater from unlined irrigation channels, storage dams, and excess water used for irrigation (flood irrigation practice; [12]). During percolation, natural soil infiltration occurs through unsaturated soil; as the effluent moves through the soil and the aquifer, it can undergo significant quality improvements through physical, chemical and biological processes.

Non-intentional natural SAT has treatment benefits in the unsaturated zone in the Tula Valley. It acts as a natural filter, and produces groundwater of acceptable quality due to the characteristics of the soil-aquifer structure, the residence time, and the history of the complex geohydrological system. Table 3 showed the historical data of wastewater and aquifer water quality variability obtained from studies performed at the site. It indicates that parameters related with salinity behavior are present in groundwater, in addition to parameters such as nitrate, and solids in dissolved phase. In contrast, the percentage removal of pathogenic organisms and emerging pollutants through unsaturated soil is greater than 50%.

There is evidence that during infiltration the vast majority of microorganisms are retained in the first few centimeters of soil [40], however their potential fate is influenced by size ranges of microorganisms (20-80 μm for helminth eggs, 1 μm for bacteria, 4-12 μm for protozoa), type of soil, and even soil organic matter content for bacteriophages (20 to 200 nm), and therefore for viruses; thus the migration of microorganisms through soil does not always allow complete attenuation.

| Parameters | Units | Wastewater (Min-Max) | Aquifer (Min-Max) | % removal (mean) |
|---|---|---|---|---|
| **Basic analysis** | | | | |
| Total Dissolved Solids, TDS | mg/L | 409-1123 | 546 -1586 | -55.5 |
| Alkalinity | mg/L | 324-600 | 256-748 | -7.8 |
| Nitrate (as N) | mg/L | 0.02-0.47 | 0.0-32 | -8014 |
| **Salinity related analysis** | | | | |
| Electrical conductivity | µS/cm | 1734-3000 | 1755 -4187 | -18.0 |
| Redox potential | mV | -51 - -37 | -79.1 - -11.0 | -38.7 |
| Sodium | mg/L | 56-215 | 103 -361 | -38.3 |
| Potassium | mg/L | 19-13190 | 10.5 -107 | 98.0 |
| Hardness Ca | $mgCaCO_3/L$ | 90-131 | 70-787 | -218.4 |
| Hardness Mg | $mgCaCO_3/L$ | 12-51 | 17 -301 | -65.7 |
| Total hardness | | 122-172 | 114-1006 | -181.8 |
| Bicarbonate | mg/L | 270-504 | 212-652 | -12.8 |
| Sulfate | mg/L | 53-2492 | 190 -3025 | -15.0 |
| **Microbiological analysis** | | | | |
| Total Bacteria count (37 ºC) | Log CFU/100 mL | 6.4-7.7 | 1.3-4.2 | 57.6 |
| Faecal coliforms | Log CFU/100 mL | 5.6-7.5 | 0.0-2.9 | 70.8 |
| Enterococci | Log CFU/100 mL | 2.3-5.9 | 0.0-1.9 | 79.3 |
| Clostridium spores | Log CFU/100 mL | 3.2-5.6 | 0.0-2.6 | 61.1 |
| Somatic Bacteriophages | Log PFU/100 mL | 2.5-4.9 | 0.0-2.8 | 52.6 |
| *Giardia* spp. | Cysts/L | 70.3-3233 | 0.0-600 | 89.4 |
| Helminth egg | Ova/L | 1.9-21.9 | 0.0-2.9 | 96.0 |
| **Emerging pollutants** | | | | |
| Clofibric acid | ng/L | < LOD | < LOD-0.39 | -- |
| Ibuprofen | ng/L | 1325-4700 | 0.05-1.46 | 99.99 |
| Salicylic acid | ng/L | 13580-72979 | 0.02-27.7 | 99.98 |
| 2,4-D | ng/L | 295-2641 | < LOD-0.48 | 99.99 |
| Gemfibrozil | ng/L | 640-750 | < LOD-0.1 | 99.99 |
| Naproxen | ng/L | 5861-16336 | 0.04-3.266 | 100.00 |
| Ketoprofen | ng/L | 82-500 | 0.02-0.83 | 99.89 |
| Diclofenac | ng/L | 1240-3424 | < LOD-3.75 | 99.98 |
| 4-nonylphenol | ng/L | 6970-38130 | 0.81-67.6 | 99.93 |

| Parameters | Units | Wastewater (Min-Max) | Aquifer (Min-Max) | % removal (mean) |
|---|---|---|---|---|
| Pentachlorophenol | ng/L | 40-110 | < LOD-0.33 | 99.81 |
| Triclosan | ng/L | 360-2880 | < LOD-22.6 | 99.83 |
| Bisphenol-A | ng/L | 700-6230 | 0.02-153 | 99.54 |
| Butil-bencilphthalate | ng/L | 125-2959 | 0.03-308 | 97.78 |
| Bis-2 ethyl(hexyl)phthalate | ng/L | 4664-70200 | 3.07-933 | 99.97 |
| Estrone | ng/L | 14-100 | < LOD-0.24 | 99.92 |
| 17β-estradiol | ng/L | 6.8-22 | < LOD-0.06 | 99.90 |
| 17α-etinilestradiol | ng/L | <LOD | < LOD-0.05 | -- |
| Carbamazepine | ng/L | 200-275 | 0.14-193 | 85.89 |

Adapted from [23, 31, and 39] (ND: Not detected LOD: Lower limit of detection).

**Table 3.** Water quality variability for wastewater and the Tula Valley aquifer and natural removal percentages (SAT)

Data recorded over many years regarding the attenuation of emerging pollutants through soil show a mean reduction of 86 percent of the chemical load in the wastewater used for irrigation (Table 3). The main attenuation processes such as adsorption and biodegradation have been confirmed in experimental studies with local soil samples, and enriched samples [23]. The most important result of this research is the observation that large amounts of suspended and dissolved organic matter in soils [41], and even in raw wastewater, improve the adsorption of emerging pollutants in soils, and therefore their final low content in groundwater; this verifies previously published results with regard to the role of natural SAT in removing pollutants [26, 42]. In fact, the sorption behavior of three pharmaceuticals (naproxen, carbamazepine, and triclosan), a plasticizer Bis-2 ethyl(hexyl)phthalate, and the surfactant metabolite 4-nonylphenol in wastewater irrigated soil, was analyzed for different soil depths sampled from the Tula Valley, showing that the potential migration of these compounds to the aquifer depends on the physical and chemical characteristics of soil, such as organic matter content, and clay/sand percentages [43, 44].

Other studies have shown that heavy metals have accumulated in soil in the Tula Valley (for example cadmium, nickel, and lead) and their retention is associated with the length of time that wastewater has been used for irrigation [45].

It should be mentioned that a large wastewater treatment plant is currently under construction to treat the MAVM's wastewater and reduce pollutant load to the Tula Valley. This plant, Atotonilco, is designed to treat 35 $m^3/s$ with a combined process (23 $m^3/s$ with a biological process and 12 $m^3/s$ with a physicochemical process) that may partially remove organic matter and the bulk of pathogens. However, the effect on soil attenuation must be evaluated as Gibson *et al.* [41] suggest that a reduction in the amount of organic matter that gets into irrigated soils may affect sorption processes, which could have an impact on the removal of emerging pollutants, pathogens, and heavy metals.

### 4.5. Impacts of wastewater irrigation in the Mezquital Valley

Reuse in the Tula Valley has functioned as a discharge route for the closed basin of the MAVM at a relatively low cost. The characteristics of the water, in terms of organic matter and nutrients have significantly increased crop productivity in the Valley and have allowed farmers to harvest up to five crops per year of alfalfa, fodder oats, tomato, barley, and maize. Resulting yields in the Tula Valley are 71 to 150% higher than those obtained with rain-fed agriculture [19]. Thus, the contribution of nutrients represents estimated annual savings of \$180 to \$200 million USD. To exemplify this, agricultural production for 2011-2012 in the Irrigation Districts of the Tula Valley reached \$418 million USD [46].

Since 81% of the main distribution canals as well as 52% of lateral distribution canals are unlined, 80.2 $Mm^3/y$ of conveyed wastewater infiltrates to the aquifer [47]. It is with this infiltration that wastewater quality is improved before reaching the groundwater through processes like adsorption or biodegradation, which depend on contact time and filtering distance. As an example, travel times from the irrigated fields to the springs are estimated to be 3 to 5 days with groundwater velocities of 0.02 to 6.0 m/d [16].

This infiltration has also incidentally recharged the Tula Valley aquifer for more than 100 years, at a recharge rate estimated at 25 $m^3/s$ and equivalent to 13 times the natural recharge [16]. As a consequence, the water table has risen from a depth of 60 meters in the 1950's to 4 meters in the southern part of the Valley and several springs with flows between 40 and 600 L/s have appeared [16]. The amount of available water with a relatively good quality allows some areas to be used to grow vegetables like tomato, lettuce, cabbage, beetroot, cilantro, radish, carrot, spinach, and parsley [16]. At the same time, surface and groundwater produced by wastewater infiltration provide drinking water to approximately 500,000 people after only treatment with chlorine for disinfection [12].

In contrast, wastewater reuse in the Tula Valley has some negative impacts on the local population and the environment. Due to the pathogens and parasites contained in wastewater, the incidence of gastrointestinal diseases has increased by more than 16 times in children living in the irrigation area, compared to children unexposed to wastewater [48]. In addition, microbial and organic pollutants have been detected in the soil matrix of the irrigation areas at various depths [41, 44]. Heavy metals have accumulated in the upper soil layer [49], and Siebe [45] suggests that eventually the retention capacity of the soil might be exceeded with the risk of groundwater pollution. Moreover, the gradual salinization of local soils has caused the loss of more than 2,000 ha of cropland [17].

### 4.6. Conventional wastewater treatment processes, control of micropollutants, and hazardous substances in water

Even though the soil filters a large amount of pollutants from wastewater with removals above 90% [12], some studies have demonstrated that in some areas the filtered water still contains bacteria (coliforms and enterococci) and viruses [40, 50]. Filtered water presents a high concentration of salts (indicated by sodium, sulfates, carbonates, bicarbonates, chloride, calcium hardness, electrical conductivity, and potassium), and furthermore, total dissolved solids and nitrates exceed the limits set by the Mexican regulatory authorities (1,000 and 10 mg/L, respectively).

At the same time, several studies [23, 31, 40, 41, 43, 44] report the presence of emerging pollutants in springs and wells, which poses a health risk to local population (approximately 500,000 inhabitants) that use the water for human consumption (Figure 5). These pollutants exhibit low removal by conventional treatment processes and thus alternative technologies, such as membrane filtration (nanofiltration or reverse osmosis), have been proposed [51]. Different studies have demonstrated that nanofiltration removes emerging pollutants, including those with low molecular weight, in particular pesticides [52], pharmaceuticals [51], and endocrine disruptors [52].

As a result, to improve the quality of spring water in the Tula Valley, a pilot plant with a nanofiltration membrane was installed in the Cerro Colorado Spring (Figure 5) [53]; The pilot plant (11.4 $m^3$/d) operated for 800 hours and included a pumping system, a prefilter, a softening unit for reducing potential scaling, and a nanofiltration module (Figure 6). The nanofiltration (NF) membrane was selected after laboratory trials on a pilot cell. The pilot plant had the instrumentation required to measure flow, pH, TDS, as well as pressure along the system. Recovery (permeate) was maintained at more than 66 % of the influent.

**Figure 5.** Cerro Colorado Spring at the Tula Valley.

Nanofiltration demonstrated its effectiveness for removing organic matter (92% of total organic carbon), salinity (60% of total dissolved solids and 75% of electrical conductivity) and 100% for selected microorganisms (faecal coliforms, faecal streptococci, *Salmonella* spp., *Clostridium perfringens*, *Giardia* spp., and bacteriophages). With respect to emerging pollutants, membrane selectivity varied from 5 to 6% for salicylic acid and nonylphenol up to more than 75% for gemfibrozil, butylbenzyl phthalate, carbamazepine, and diclofenac. Treated water (permeate) met the limits for drinking water and thus it could be considered suitable for human consumption.

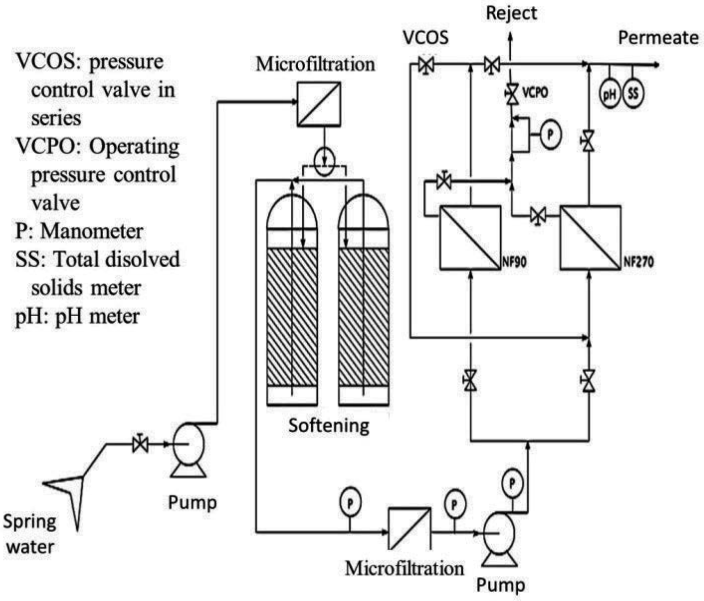

**Figure 6.** Flow diagram of the nanofiltration pilot plant at the Cerro Colorado Spring, Tula Valley.

Based on such studies, filtered water from the Tula Valley is being considered as a potential source for supplying drinking water for Mexico City and studies have determined that 6.5 $m^3$/s may be sourced from local groundwater [54].

## 5. Forthcoming expectations and recommendations

Findings confirmed by 15 years of research into the complex Tula Valley hydrological and hydraulic system, are:

- Wastewater reuse for irrigation has proven to be an alternative in the water-scarce region of Tula Valley.

- Agricultural irrigation in the Tula Valley using raw wastewater from the Metropolitan Area of the Valley of Mexico has been performed for more than 100 years and several studies have demonstrated that complex phenomena occur.
- One of these is the natural SAT in the saturated soil zone, which even occurs today after a century of irrigation, mainly in terms of the retention of typical pathogenic organisms and emerging contaminants in wastewater of urban origin.
- The observed level of natural removal through filtration by soil exceeds the expected removal levels from conventional wastewater treatment, not only for emerging contaminants, but also for microorganisms that are difficult to remove by chlorine disinfection.
- Non-intentional aquifer recharge with water purification by natural infiltration, achieved through agricultural reuse of untreated wastewater, has provided new water sources for the local population with the potential to supply water for human consumption to the large city from which comes the reused wastewater originates.
- Advanced treatment studies conducted by our research group have shown that it is possible to treat water from aquifer for safe water supply.

There is no doubt about the benefits of wastewater reuse for irrigation, but some potential impacts should be considered:

- Even though the soil matrix retains pollutants, the limit of the soil retention capacity remains uncertain, largely for metals and emerging compounds.
- The content of organic matter in soil has been a key factor in the natural attenuation of water pollution, however, the impact of future changes in the quality of water for irrigation purposes in Tula Valley, may affect removal capacity.
- Soon, the Atotonilco WWTP will supply wastewater to the irrigation canals with a lower content of organic matter and nutrients. These are factors which have previously favored the natural process of the SAT and the development of agricultural activity in the area. These reductions may affect complex physicochemical processes in the future, and may have impacts on soil and groundwater quality that cannot be predicted.
- The use of treated wastewater for irrigation, will allow the growing of crops normally eaten raw, which up till now has been forbidden by national legislation. Other benefits will be the reduction of direct exposure of farmers to pollutants in untreated water.
- Finally, with regard to national and international legislation for irrigation, it is evident that local studies are required for establishing permissible limits. This is because existing guidelines require wastewater treatment levels which are economically onerous, mainly for developing countries, and moreover, do not include limits for other pollutants present in urban wastewater (pharmaceuticals and personal care use products). Wastewater will become more and more attractive for agricultural reuse, given the current and future problems of water scarcity.

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# Impacts of Abattoir Waste-Water Irrigation on Soil Fertility and Productivity

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Additional information is available at the end of the chapter

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## 1. Introduction

Water is the most precious resource that exists naturally on the planet earth; yet, global fresh water is only less than 3% and increasing population density [1] has been increasing the pressure on global fresh water resources [2]. More importantly, impacts on freshwater quality and quantity are enormous in the current era of industrialization, modernization, over exploitation, and poor resource management practices.

Increase in global population and decrease in the availability of clean water is limiting human activities, especially industries. Most industrial processes require enormous quantity of water, which almost equally discharges wastewater [3]. Wastewater emerges from both domestic and industrial sources, untreated discharges of wastewater often contains significant amount of pollutants, nutrients and pathogens [4]. Industrial processes need huge quantity of water to meet the quality of products with customer satisfaction. The major industrial sources of wastewater include canneries, milk dairies, Sugar factories, Breweries and distilleries, Beverage industry, Meat industry, Fertiliser manufacture, Pulp and paper, Tanneries and Yeast manufacture [5]. Among the industries generating high volume of wastewater, meat industries act as a major source with the increase in meat intake by people. Agriculture and allied industry consumed the largest volume of water with more than 50 % of Australia's water consumption in 2009-10 [6].

Unsafe water and sanitation practices account for more deaths worldwide from diseases than any war claims [7]. One quarter of the world's population is without safe drinking water [8]. To overcome the pressure on fresh water sources caused by the industry, sustainable alternative methods are needed which will reduce the pressure on global fresh water resources as well as to meet the demand of water for households, industries and agriculture [9]. There is a wide range of environmental challenges facing the industrial sector globally, especially in the sustainable management of wastewater. With stringent environmental laws in most of the developed nations, industries needed to adopt the existing cost-intensive treatment methods including phytoremediation, land treatment and constructed wetlands [10, 11].

Therefore, development of a low-cost wastewater management technology is needed to treat the wastewater from various sources. Among the low-cost technologies, landfilling has been the most popular and widely followed technology for its convenience in handling and easy maintenance [12]. However, long-term discharge of effluents builds up the levels of nutrients, organic matter and heavy metals posing different kind of threat in terms of land degradation and pollution of surface and underground water resources. Hence, growing plants on the wastewater treated soils can emerge as a sustainable measure towards water resources management, which can be termed as phytoremediation. This approach is not only energy efficient and aesthetically pleasing method of remediating sites with low to moderate levels of contamination but can also be used in combining with other more conventional methods. It will provide potential solutions to reduce the cost of meat production and it will also help to protect our natural resources for the future generation. Overall fresh water consumption is reduced by adopting water efficient techniques and water reuse where water resources are scarce [13]. This book chapter aims to describe the effects of wastewater irrigation on soil fertility and productivity, assessment, mitigation, and farm nutrient budget based on wastewater driven nutrient.

## 2. Global wastewater scenario

Around 90 per cent of wastewater produced globally remains untreated, causing widespread water pollution. An approximate estimate of global wastewater production is about 30-70 cubic meters per person per year causing significant impacts on the natural environment [14]. Globally, meat industry wastewater act as a major source of industrial wastewater, for example in Australia, meat industry generates an average of 7225 ML /year. The concerns over conserving water resources have led to new innovations for the sustainable management of Australia's wastewater into usable water resources. In the last 30 years, reuse of wastewater for agriculture has been increased due to the decline in fresh water sources, dry weather, heavy runoff loss, and overexploitation [15]. The sources of wastewater are illustrated in Figure 1.

### 2.1. Wastewater production

Global water consumption is doubling every 20 years and by the year 2025 two out of three people in the world will be living under water scarcity, especially in under developed and some developing countries [3]. Over 1.1 billion people across the globe lack access to safe drinking water and 2.4 billion to adequate sanitation. As a result, a child dies every 15 seconds from water related diseases [16, 17]. The health of a person depends on the quality and quantity of water for sustaining good health and vigorous life. Since agriculture, households and

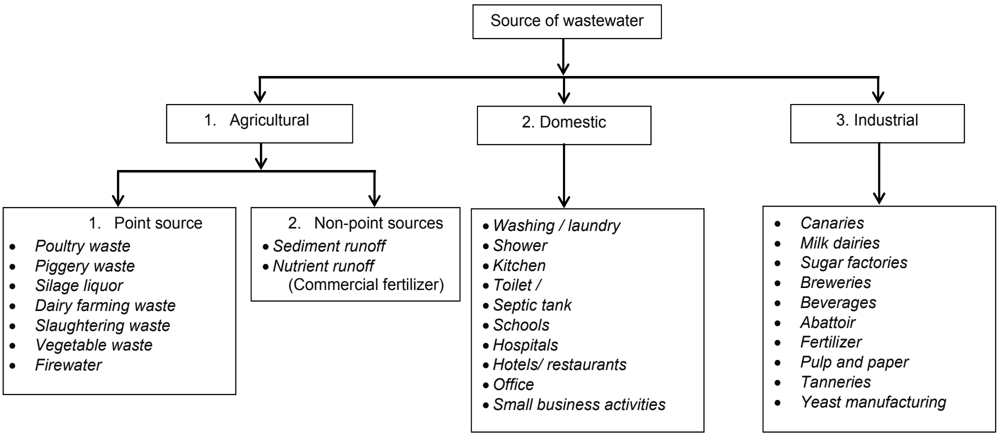

**Figure 1.** Sources of wastewater streams

industries are the three sectors which consume majority of water, they generate large volume of wastewater. For example, in Australia domestic wastewater aloneis being produced at 44165 litters per person per year [18], country's total of 1040.3GL/year [6].

Wastewater which has been used at least once, and has thereby been rendered unsuitable for reuse without treatment is being collected and transported through sewers [19]. Industrialization positively increased the number of industries around globe, and this proficient growth has significant impacts on the natural environment. Since, Australia is among the driest countries on the globe, having very minimal river runoff (about 1%) [20], it's necessary to re-use all the wastewater discharged to natural environment.

### 2.2. Characteristics of different types of wastewater

It is important to characterise wastewater before it is being re-used for many purposes. The nature of wastewater depends on the industry type and material processed. For example, the wastewater discharged from abattoir is different from winery; hence the understanding on chemical characteristics is important. Abattoir wastewater derives organic loads from different sources. Animal manure contributes significant amount of pollutants to the abattoir effluent containing N, P, and organic carbon [21]. In comparison with other wastewater sources, abattoir wastewater stream possess the highest concentration of organic load, with increased COD (8000 mg/L), proteins (70 %) and suspended solids (15-30 mg/L) [22].

Piggery effluent contains 158-1025 mg/L of N; 11-123 mg/L of P; 97-1845 mg/L of K and 103-2870 mg/L of Na with other beneficial micro nutrients [23]. According to the APL-AMIC –projects report, water usage, feed grain supply and managing nutrients in the piggery effluents are the major environmental challenges faced by Australian piggeries [24]. Piggery effluents and by-products can be used as valuable alternatives for fertiliser's agricultural production. Wastewater discharged from wineries is rich in nutrients; it contains 1-128 mg of N /L; 1-33 mg of P /L; 19-1250 mg of K /L and 18-880 mg of Na /L [23]. Organic load or waste load in the winery wastewater increases the nutrient content (sodium and potassium) and BOD of the wastewater, which may lead to salinity and sodicity [25]. Dairy farm generates large volume wastewater with rich in nutrients especially N and P. Dairy farm wastewater comprises of urine, faeces, chemicals from cleaning, and solid waste (cow dung). This contributes 15-200 mg of N /L; 11-160 mg of P /L; 11-160 mg of K /L [26]. Typical characteristics and nutritional composition of different agricultural industries wastewater is shown in Table-1.

| Constituents | Domestic | Textile | Abattoirs | Piggery | Dairy effluent | Olive mill | Winery |
|---|---|---|---|---|---|---|---|
| SS (mg $L^{-1}$) | 350 | 245 | 2000 | 447 | 28-1900 | 2.8-126 | 60-2000 |
| TDS (mg $L^{-1}$) | 850 | 1130 | 3500 | 3100-8600 | 138-8500 |  | 500-2200 |
| K (mg $L^{-1}$) |  |  | 100-400 | 97-1845 | 11-160 | 17100 | 19-1250 |
| Na (mg $L^{-1}$) |  |  | 20-150 | 623<br>(103-2870) | 60-807 | 400 | 18-880 |
| N (mg $L^{-1}$) | 50- 70 |  | 100-150 | 854<br>(158-1025) | 15-200 | 0.09-3.2 | 1-128 |
| pH |  | 10.2 | 7.3 | 7.5-8 | 5.6-8 | 4.2-7 | 4-10 |
| P (mg $L^{-1}$) | 20 | 3.4 | 100-400 | 109 (11-123) | 11-160 | 1.1 | 1-33 |
| $BOD_5$ (mg $L^{-1}$) | 300 | 227 | 1300-7500 | 40 | 320-1750 | 1.5-100 |  |
| COD (mg $L^{-1}$) | 240-440 | 2120 | 100-250 |  | 1120-3360 | 6.4-162 |  |
| TOC (mg $L^{-1}$) |  | 2.5 |  |  | 201-6664 |  |  |
| Oil & Grease (mg $L^{-1}$) | 150 |  | 100-1000 |  | 68-240 | 2.26 |  |
| References | Huang *et al.*, 2010. [60] | Yusuff. 2004. [61] | Mittal. 2004. Damien Batstone., 2012. [31,62] | EPA-SA., 2009. [23] | EPA-SA., 2009. Marimoli et al., 2011. [23,26]. | Anastasiou, 2011. [63] | EPA-SA., 2009. [23] |

SS – Suspended solids; TDS – Total dissolved solids; BOD – Biological oxygen demand; COD – Chemical oxygen demand; TOC – Total organic carbon

**Table 1.** Characteristics and constitutes of wastewater from selected sources

## 2.3. Wastewater disposal and treatment

Treatment of wastewater, before reuse is most important to avoid the excess load of contaminants such as solids, organic matter, nutrients and pathogens [27]. For example, untreated abattoir wastewater is unsuitable for reuse or discharge into receiving environment. It will cause serious environmental hazards in the receiving environment such as eutrophication, land degradation, nutrient leaching, ground water contamination, greenhouse gas emission and effects on ecosystem value; hence proper reduction in pollutant levels in the prior stage is essential. The various environmental impacts of abattoir wastewater disposal methods are described in the table 2.

| Disposal methods | Impacts |
|---|---|
| Evaporated pond | • Odour emission<br>• Toxicants<br>• Pathogens (disease causing agents)<br>• Organics and inorganics loads |
| Irrigation<br>-landscape<br>-agriculture | • Odour<br>• Soil contaminants<br>• Persistent of soil pollution in soil<br>• Potential for carrying heavy metals to food chain<br>• Bioconcentration, Bioaccumulation, Biomagnification |
| River<br>Steams<br>lakes | • High load of organic and inorganic pollutants<br>• High load of BOD<br>• Pathogenic organism<br>• Unsuitable for irrigation<br>• Odour<br>• Eutrophication<br>• Death of fishes<br>• Loss of biodiversity / decrease ecosystem value |
| Coastal / ocean | • Loss of fish breeding<br>• Odour<br>• High load of organic and inorganic pollutants<br>• Climate change<br>• Global warming |
| Infiltration<br>-Natural<br>-Artificial | • Ground water contamination<br>• Loss of ground water quality<br>• Aquifer clogging<br>• Long term impacts in the flora and fauna. |

**Table 2.** Wastewater disposal methods and their impacts

Abattoir wastewater must be treated before it reaches the receiving environments, to maintain minimum pollutant standards [28]. Effective abattoir wastewater treatment methods should remove the pollutants, nutrients, organic load, fat, oil crease, blood and pathogens from the wastewater to ensure the low level of toxicants in the final discharge effluent [29]. Abattoir wastewater treatment involves various methods to treat the meat industry effluents and to retain the bio-wealth of an ecosystem.

There are three major types of treatment technologies (primary, secondary, tertiary) that can be used to treat the abattoir wastewater (Figure 2). A typical abattoir wastewater treatment plant should have three kinds of storage system or pond to reuse the treated wastewater into irrigating agricultural crops, the first one is anaerobic pond, followed by aerobic /facultative ponds then a polishing / irrigation pond [29]. Each wastewater treatment technique is evaluated in the form of its merits and demerits by economic feasibility, technical availability, and socio–cultural acceptability. This kind of evaluation is very important to assume the wastewater recycling method to current and future.

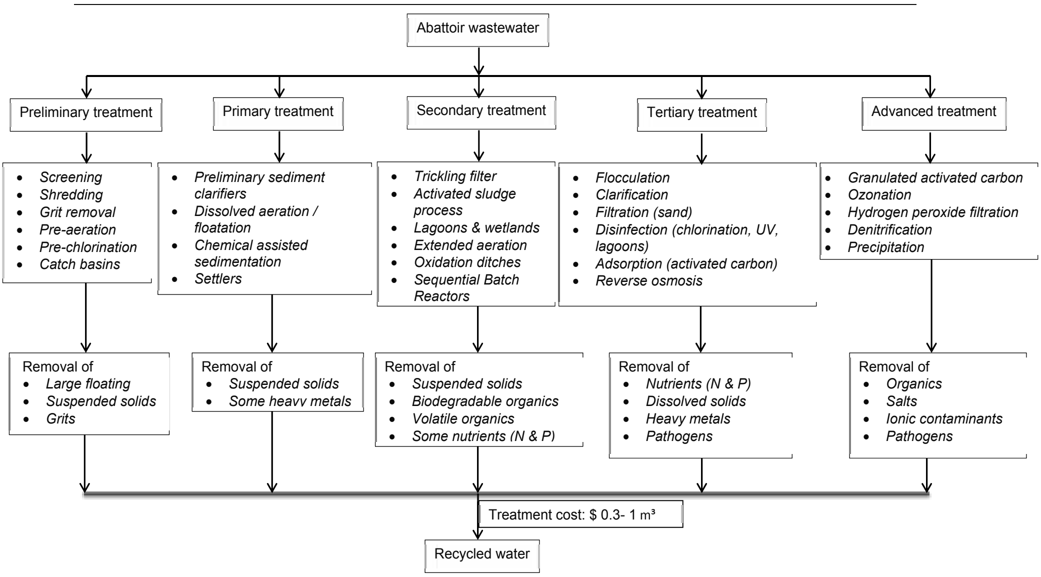

**Figure 2.** Wastewater treatment methods

Pre-treatments include screening, catch basins, floatation, equalization, and settlers. A primary treatment includes screening, dissolved air flotation (DAF) and flow equalisation [30]. Pre-treatments are processes that remove gross solids; coarse suspended floating matter and primary treatments remove readily settleable solids, most commonly by sedimentation [31]. Pre-treatment methods can be used to minimise the organic load and BOD in the wastewater. Pre-treatment methods such as screening and sedimentation helps to reduce 60% of solids and 25-35 % of BOD load from wastewater [32]. Anaerobic process includes lagoons, anaerobic contact anaerobic filter, anaerobic sequencing batch reactor (ASBR), up-flow anaerobic sludge blanket (UASB). An aerobic system includes aerated lagoons, activated sludge process, oxidation ditches, sequencing batch reactors and trickling filters. The advantage of lagoons in the wastewater treatments is high efficiency in organic material ($BOD_5$) removal, at the same time very poor in N and P removal [33].

The pollutants that remain after primary treatments can be removed by secondary treatment methods, including fine suspended solids, colloidal and dissolved organic matter by biological / chemical treatment by aerobic or anaerobic process. Anaerobic contact reactors (ACR) are the best treatment system that reduces the BOD levels by 90% and volatile solids removal by 41-67 %. The issue with anaerobic reactors is odour generation, which can be minimised by installing synthetic floating covers on the lagoons, to avoid odour as well as to trap biogas [34]. Temperature is one of the limiting factors of anaerobic lagoon, which determine the efficiency of lagoons and most anaerobic lagoons are more effective when temperature is above 21ºC [35]. In many countries aerobic-anaerobic stabilisation ponds are most widely used to treat abattoir wastewater and its efficiency varies from place to place, for example, in New Zealand, the ponds remove less than 35 % of N [36].

Anaerobic lagoons can be an effective wastewater treatment technology, for its ability to reduce BOD 97%, COD 95% and SS 96 % [37]. Hence, it is considered as the best available treatment technology for the slaughterhouse wastewater, since meat industry wastewater is rich in organic pollutants [38,39]. This method is most popular in countries like USA and Australia mainly because they have suitable climate and large land availability to adopt anaerobic lagoons in wastewater treatment [34]. In meat industry wastewater, N and P can be removed biologically using granular sludge method, with a removal efficiency of TN-86 %, TP-74 % and COD-68 % [40].

Nutrient removal is an important treatment process in slaughterhouse wastewater treatment and is the final or tertiary stage treatment. Nutrients such as N and P are introduced to the receiving area if industries fail to adopt nutrients removal before discharge into sites. Majority of the industries reuse their wastewater for various purposes especially irrigating the crops/ lawn. Environmental factors of an effective treatment system are shown in figure 3.This helps to maintain soil fertility, productivity and sustainability whereas discharge into river, ocean need an appropriate nutrient removal techniques to reduce the nutrients concentrations to minimum acceptable level. Advanced treatment processes (Granulated sludge, Sequencing batch reactors, integrated aerobic-anaerobic film reactor, Aerobic-anaerobic stabilisation pond, Anaerobic treatment methods) helps to reduce the concentration of nutrients in the effluent, most essentially N and P. Eco toxicity level of the wastewater quality standards and their usage are summarised in the Table 3.

| **Parameter** | **Irrigation** | **Sewer large city** | **Sewer small town** | **Coastal surface water** | **Inland surface water** | **Reuse non potable (a)** |
|---|---|---|---|---|---|---|
| BOD (mg $L^{-1}$) | Site specific | 4000 | 600 | 10 | 10 | 100 |
| pH | 6.5-8.5 | 6.0-10.0 | 7.0-9.0 | 5.0-9.0 | 6.5-8.5 | 5.5-8.0 |
| TDS (mg $L^{-1}$) | 1000 | NA | NA | NA | 500 | 1000 |
| Coliforms (Org 100 $mL^{-1}$) | 1000 | No limit | No limit | 1000 | 200 | 1000 |
| TN (mg $L^{-1}$) | Site specific | 500 | 100 | 15 | 10 | 150 |

(Source: MLA-RPDA-1998); a) Typical for non-potable reuse.

**Table 3.** Abattoir wastewater disposal quality

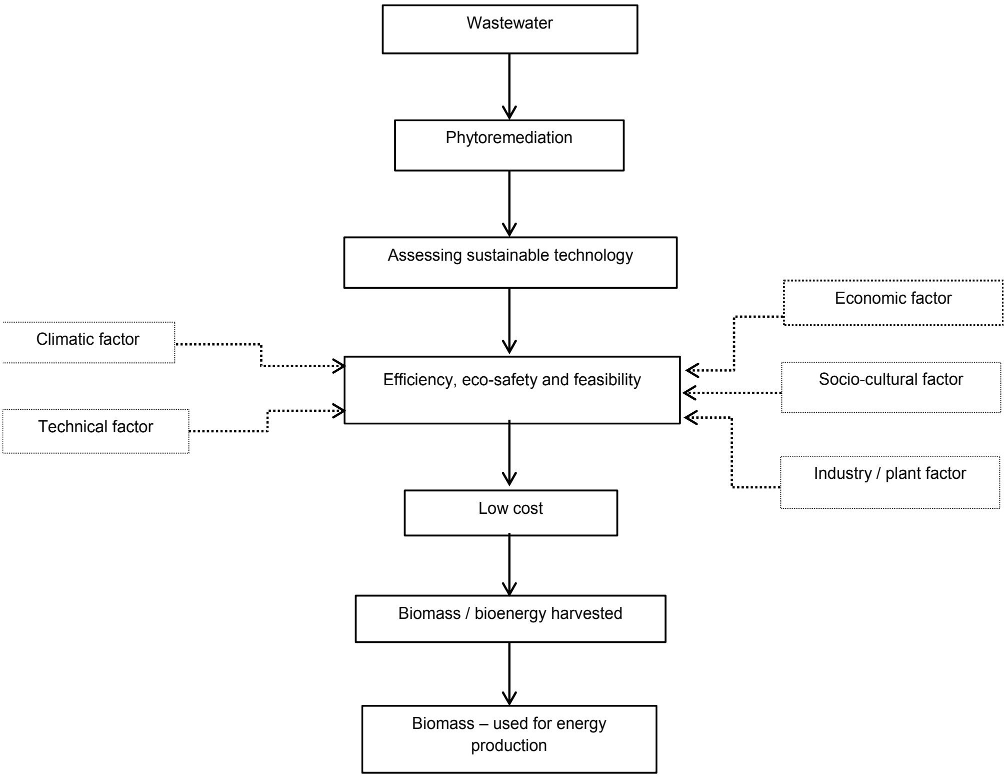

**Figure 3.** Factor influencing wastewater management plan involving phytoremediation

## 3. Effect of wastewater irrigation on environment and soil

The impacts of the abattoir wastewater on the natural environment can be broadly classified into three categories viz, health and social impacts, economic impacts and ecological impacts.

### 3.1. Health and social impacts,

#### *3.1.1. Air pollution*

Air related problems in abattoir waste water can be caused by dust, flies and odour which will have strong impacts on the adjacent areas. Abattoirs are generally known as "dirty" due to various pollutants or dust generation activities such as rendering and slaughtering [41].

#### *3.1.2. Disease causing pathogens*

Wastewater carries diverse microbes that can contaminate the water sources [42], leading to the spread of pathogens from one place another [31]. This may lead to a wide range of diseases such as cholera, typhoid, and dysentery [43].Wastewater discharges from slaughterhouse without proper disinfection, leads to occurrence of meat based infections due to the high populations of *E. coli* and *Salmonella sp.* [44].

### *3.1.3. Odour and noise nuisances*

Odour is a most common issue associated with abattoir wastewater [45]. Odour is a problem, if abattoir wastewater is not treated completely to control the biological oxygen demand (BOD), which may result in the anaerobic activities [34,46]. The majority of the meat industry sites reported that emitting nuisance odour and noise is a serious issue for the local community. The most common sources of odour emissions from the meat industries are:

- Wastewater storage pond & wastewater treatment areas.
- Wastewater irrigation sites /land
- Rendering and by-products plants
- Truck deliveries for rendering
- Animal wastes such as urine and faeces

The most common sources of noise pollution are:

- Boiler steam blowdown
- Bellowing cattle

### *3.1.4. Aesthetic amenity*

Aesthetic amenity / loss of aesthetic value can be observed in majority of the industrial zones and disposal sites. It has significant impact on the loss of land value and aesthetics, ultimately reducing further urban development. Abattoir wastewater has disruption of recreational use of the waterways due to pollution, for example, odour nuisance and aesthetic amenity [46].

## **3.2. Economic impacts**

### *3.2.1. High cost*

Most abattoir industries are established away from the urban areas due to the cost of land and high capital requirement for waste and wastewater disposal [28]. Abattoir wastewater significantly increases the cost for wastewater treatment, disposal and reclamation of contaminated sites [47].

Estimated cost disposal methods

$1.95/kL discharge into sewer

$1.55/kL discharged into waterways

$0.60/kL discharged into land

Abattoir wastewater treatment and disposal requires high cost. For example, in Canada about Can$ 0.70-1.60 / $m^3$ and in the United States, about is US, $20 / 0.159 $m^3$ or US $30-40 / $m^3$ are being paid by the meat processing industry for the disposal of beef slaughter residues [38]. Most small and medium abattoirs do not have the tertiary and advance treatment facilities, due to high capital involved in these methods [31, 38].

#### *3.2.2. Loss of land value:*

Disposal of poorly treated and untreated wastewater in a land will reduce the value of land both by cost and productivity. Abattoir wastewater is mostly treated mechanically and also biological treatment system in ponds. Any leakage of effluents from ponds may result in serious ground water pollution due to infiltration of nitrate and phosphate [46]. Since abattoir wastewater discharges carry significant amount of pollutants their disposal to land need high investment, which may result in the loss of land value [34].

### 3.3. Ecological impacts

#### *3.3.1. Algal blooms or microbial blooms or toxic algae*

Disposal of abattoir wastewater without proper treatment leads to the deterioration of the water quality. Wastewater with its rich nutrient content can cause profuse growth of algae (algal blooms) that kills fish and other aquatic flora and fauna [34]. Abattoir wastewater with its rich nutrient content (nitrate and phosphate) from animal manure and various processes directly influences the growth of algae in the aquatic ecosystem. Prolific growth of algae is called as algal blooms, posing a direct threat to ecosystem.

#### *3.3.2. Soil contamination:*

Soil contamination is caused by discharges of poorly treated wastewater, which may contain heavy metals, organic compounds, inorganic compounds, soluble salts and pathogens. In the absence of effective management strategies, pollutants find pathways to enter groundwater and food chain causing serious threats to natural environment and human beings. Wastewater can be used for irrigating the crops, but the concentration of pollutants and nutrients load above threshold level will cause serious soil problems including soil salinity [48]. Inappropriate nutrient management in the wastewater system leads to deposition of excess amount of nutrients in the disposal sites and further causes potential effect on soil fertility and productivity. Continuous discharge of abattoir effluents over the same site results in soil contamination, thereby affecting soil biodiversity and productivity. Consequently, productive land and clean water resources are becoming scarce due to the following issues [29]:

- Wastewater from stabilisation pond, effluent evaporation-Increased salinity
- Surfactants derived from equipment cleaning-Increased alkalinity
- Organic / solids / manure transfer to wastewater and wetlands-Increased turbidity

Continuous disposal of effluent system can create a chance for ground water contamination due to nitrate leaching, and many other direct and indirect impacts can also occur [33]. Universally, land contamination is caused by industrial, mining, domestic and municipal wastes, and in Australia industries and mining are the two major sectors of soil contamination.

### *3.3.3. Loss of biodiversity*

Discharge of untreated abattoir wastewater can cause serious threats in the receiving environments, altering the micro and macro environment of the receiving lands. The disposed nutrients and other pollutants can cause spatial and temporal heterogeneity in benthic populations and also preponderance of organisms such as oligochaetes and diptera which can also affect human beings [49].

Abattoir wastewater discharged into river can greatly impact the species diversity and development of aquatic organisms. The presence of high BOD will heavily impact on spatial and temporal heterogeneity of macro invertebrates [49]. Bioaccumulation and biomagnification of contaminants in in fishes present in abattoir effluent discharged aquatic ecosystems can affect a whole food cycle or food web and pose serious threats to the native flora and fauna [46].

### *3.3.4. Sources of heavy metals*

Untreated wastewater discharged in landfill sites carry heavy metals which can affect the soil properties. Abattoir wastewater acts as a source of major nutrients (N and P) and micronutrients such as calcium, sodium, magnesium, sulphur and iron and trace amount of heavy metals such as cadmium, cobalt, nickel, copper and chromium [38].

### *3.3.5. Climate change and global warming*

Meat production is a considerable source of global greenhouse gases emission (GHG), emitting methane, nitrous oxide and carbon dioxide through various stages. Livestock farming is one of the main activities responsible for GHGs emission around the globe [50]. GHGs are emitted by direct energy consumption and indirectly by feedstock production, herding, movement of animals, product transport, slaughtering, cleaning, and dressing the animal product, waste and wastewater.

Meat consumption will be high in 2020 and more consumption growth projected by 2050; predominantly in Asia and Pacific [44]. In the recent years, meat production and consumption has been increasing considerably, and predicted to peak in 2020. Global per capita meat consumption is projected to increase from 32.9 kg /rwt 2011 to 35.4 kg /rwt in 2020 [44]. A recent study at European Union states that ruminants (cows, sheep and goats) have the highest carbon footprint [50]. Total net GHGs emission of EU livestock production was estimated at 661mt of carbon dioxide equivalent ($CO_2$-eq) which is about 9-13 % of total GHGs emission for the EU agricultural sector; of those 23% methane, 24% nitrous oxide, 21% $CO_2$ (Energy use), 29% $CO_2$ (land use).

A considerable amount of GHGs emitted by the global animal industry, which is more than all the cars in the world together and large part of that 18 % nitrous oxide and methane emissions; both of these gases have a far more powerful greenhouse gas effect than carbon dioxide [51]. Livestock sector accounts for 5-50% of total contribution, but it may vary from place to place [52]. The overall contribution consists of pigs-0.4%, sheep-3.4%, cattle-2.7%, and beef cattle-11.2%, which on an average emits 554kg $CO_2$-e/tonne hot standard carcass weight [47].

## 4. Nutrient management in wastewater irrigated soils

### 4.1. Wastewater driven nutrients

Large quantities of water are used in meat industry to wash the carcasses of the slaughtered animals and to clean the equipment's in abattoirs. The wastewater generated during these processes contain high organic loads, fat contents and concentrations of N, P and Na. Majority of the wastewater undergo primary and secondary treatments before being released into the environment. The discharged effluents can be used for irrigation as it contains free source of nutrients which potentially boosts production and also reduces fertilizer inputs. Nevertheless, proper N management is needed for this purpose to minimise possible groundwater contamination. Other environmental concerns include the increase in dissolved salts causing soil salinity or Sodicity and accumulation of P in soil. Phytoremediation can be a viable cost effective remediation technique to effectively manage nutrients in soil and prevent the water resources from contamination. By cultivating suitable plant species in the wastewater irrigated land, excess nutrients can be phytoextracted by the plants for growth. In the process, a large amount of biomass can be produced for energy generation or as a feed source for grazing animals.

### 4.2. Nutrient cycling in wastewater irrigated soils

Understanding of nutrient cycling in a wastewater irrigated ecosystem is necessary to avoid nutrient loss to the environment. Nitrogen cycle: The wastewater from slaughtering house contains nitrogen in organic forms; this is converted to ammonia by ammonification ($NH^{4+}$). This process is enhanced by bacteria in anaerobic conditions. Ammonia further oxidised in to nitrite and nitrate by nitrification process with the help of nitrifying bacteria. At the end, nitrate converted into nitrogen gas by denitrification activity in the presence of facultative microorganisms. This is the typical N cycle in an abattoir wastewater irrigated ecosystem. Similarly, (Phosphorus cycle) P occurs as both organic and inorganic (phosphate) forms in the wastewater discharged from abattoir. With over 80 % of P occurring in the organic form, plant growth depends on the conversion of organic P in to inorganic forms. In general, P cycle in wastewater irrigated soils is most complicated as compared to N due the phosphate precipitation or accumulation.

### 4.3. Nutrient budgeting

Nutrient budget is an accounting approach combining the cumulative effects of nutrient inputs, uptake and deposited, which can help manage nutrients by identifying production goals and opportunities for improvements in nutrient use efficiency, and thus reduce the risk of off-farm nutrient impacts [53]. Nutrient budgeting for a wastewater treated ecosystem is more important than a farm nutrient budget. Wastewater from the treatment pond (open-pond treatment) can be used as irrigation water for fodder crops grown in the land treatment site. Abattoir wastewater typically contains a high concentration of nutrients, such as N 250 mg/L and P 30 mg/L. Annual nutrient loading used for the mass balance was calculated with the following equation.

Nutrient uptake=nutrient requirement per kg of biomass* total biomass produced

Nutrient input=nutrient concentration/L * Total amount of irrigation

The nutrient budgeting helps to minimising environmental impacts such as nutrient loss to atmosphere, leaching and overdose and efficient nutrient management for a sustainable production. Abattoir wastewater irrigation considerably increased the total dry matter yield, and nutrient uptake in soils. Dry matter production and nutrient uptake were proportional response to the rate of irrigation applied. Hence, an effective recapture all the nutrients that are discharged from agricultural industries is possible, thereby helps to meet a significant proportion of this requirement. Farm nutrient budget can be calculated using information obtained from nutrient input or wastewater irrigation rate-plant uptake – and soil test. These are the essential tools to calculate the effective nutrient budget to avoid nutrient loss to environment.

### 4.4. Plant productivity in wastewater irrigated soils

Abattoir wastewater irrigation considerably increases nutrient uptake in soils and the resultant total dry matter yield. Sparkling *et al* [54] noticed that wastewater irrigation significantly increases the annual and total herbage production and by up taking high N and P from soils. Similar results obtained by [55] concluded that wastewater irrigation has positive impacts on plant growth and development (crop height).

### 4.5. Case study

A recent study on nutrient budget of an abattoir wastewater irrigated soil showed the effect of long term abattoir wastewater irrigation on soil fertility (Figure 4). However, growing suitable plants for fodder production and bioenergy generation can help the industry to get additional benefits. The study site covers 32 hectare (16 ha currently irrigated), and receives annually about 216 megalitre (ML) of abattoir wastewater. This wastewater contains 250 mg/L of N and 30 mg/L of P. The land treatment site has received a total of 2025kgN/ha, 405kg P/ha and 1350kg K/ha plus trace elements. In overall, this site was loaded with 32.4t N, 6.4 P and 21.6t of K every year. Dry matter production and nutrient uptake were proportional to the rate of irrigation applied. The rate of application at the land treatment site was 216 megalitre (ML)/year and the total dry matter production was 110t in 2012. A total of 6t N, 1.3t P and 4.7t K respectively, was removed by herbage as nutrients uptake each year. This represents approximately 10% of that total applied.

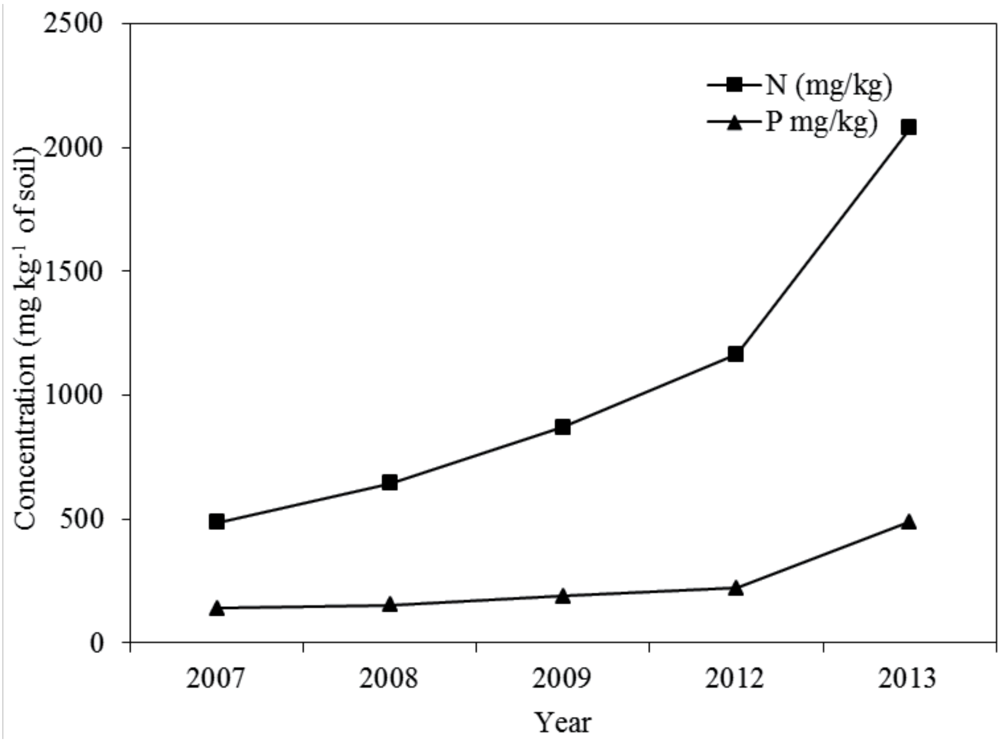

**Figure 4.** Effect of long-term abattoir wastewater irrigation on soil fertility

## 5. Sustainability concepts

It is most essential that industries need to adopt various best practices / low cost technologies to reduce their water use and cost [34]. Irrigation of wastewater is a potential low-cost approach of wastewater management and can act as a good source of nutrients for infertile soil [34]. Australia, with several meat based industries need to manage the animal wastes and effluents with low cost technology [4]. The amount of organic load, N and P, and organic carbon concentration can be reduced by prior collection of manure before wash down, which will reduce effluent loading with high concentration of pollutants [24]. Phytoremediation of abattoir wastewater is a suitable technology to manage nutrients and metals [56]. Abattoir wastewater is a richest source of N and P; hence it can be treated as an alternative source of nutrients provider for poor fertile soil [56, 57]. The following steps are important for waste reduction and low –cost wastewater treatment techniques,

- The discharged wastewater should not exceed the acceptable level nutrients and pollutants.
- Microbial community should be eradicated through disinfection to ensure no pathogens and minimise bio threats.
- The environmental standards (legislation/law) defined by the state environmental authority / EPA should be strictly followed.
- Pollution levels to be reduced through various treatment techniques to retain the environmental quality.
- Nutrients (N and P) levels are maintained in the permissible level of discharge.
- To avoid odour emissions a considerable amount BOD to be reduced.
- Removal of organic, solids, fats, oil and grease to be done through various waste treatment process.

It is very important to ensure that “zero emission” standards of pollutants in the abattoir wastewater disposal are most satisfactory for various reuse process. Abattoir wastewater treatment system and its efficiency are directly influenced by various factors. Low cost / cost effective treatment technologies, available space / site, site sensitivity to odour, characterisation of treatment system, labour availability / mechanical energy, electrical energy / power, transport facility and climate these driving force applicable to vary in place to place [58].

## 6. Conclusions and research needs

Globally re-use of wastewater has been steadily increased in the volume of water in crop production. Wastewater irrigation fulfils 1% of the Australian agricultural water demand by re-use. Wastewater acts as both water source and nutrient supplement. This is added benefit to agricultural sector especially water scarce region. This proposed sustainable concept illustrated in Figure 5, Phytoremediation of contaminated land with abattoir effluents using high biomass producing plant species can be a cost effective technology to convert contaminated lands into cultivable land. Consequently the plants used not only act as remediators, but the biomass produced can also be used for energy production, paper production and feed for grazing animals. The Australian National Water Commission-2011[59] water initiative encourages various wastewater reuses and recycling research, and development programs especially cost effective technology to meet the national water demand both current and future. Wastewater reuse is an important component of sustainable water resource management, water reuse from various wastewater sources after removing the pollutants, nutrients and pathogens provide scope for water security.

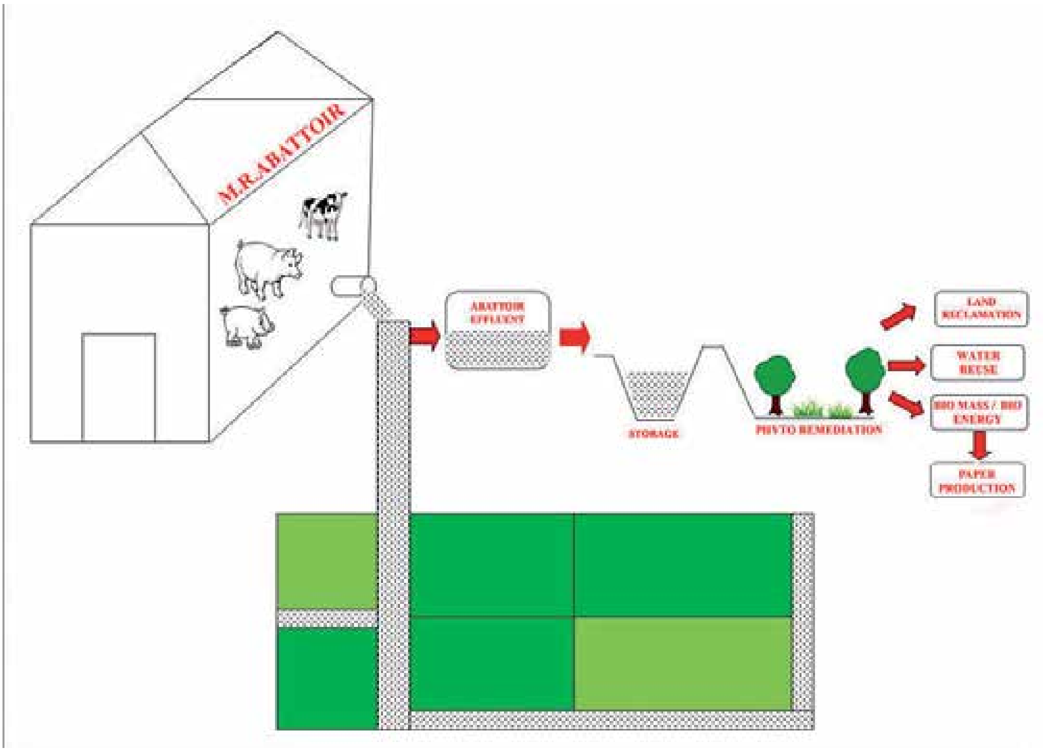

**Figure 5.** Conceptual framework of an effective low cost treatment plan for abattoir wastewater

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# Use of Hydrological Modeling Techniques to Evaluate, Develop and Enhance Irrigation Potential of a Humid Subtropical Watershed

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Hamza Farooq Gabriel and Amjad Nabi

Additional information is available at the end of the chapter

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## 1. Introduction

Water is essential and basic necessity of life. Water utilization can be categorized for domestic/municipal consumption, industrial usage and irrigation purposes, notwithstanding its necessity for ecological systems. Globally 69% of fresh water is withdrawn for agriculture purposes, 23% for industry and 8% for domestic use (J.Van.H et al 2002) [1]. Water has become a scarce natural resource whose equitable management for all socioeconomic development is essential. Irrigation is essential component for agriculture production and all developing countries are dependent on it. During 1997-1999 in developing countries two fifth of crops were provided by irrigated land (FAO, 2002a) [2]. Similarly during 1997-1999 in developing countries 59% of cereal production was obtained through irrigation (Burke et al, 2003) [3]. All over the world excluding Europe and North America agriculture sector is the largest user of water (FAO, 2002c) [4]. During 2000 worldwide 70% of water withdrawals and 93% of water consumption was done for agriculture whereas water consumption for industry and municipality use is elaborated in Figure 1 (FAO, 2004) [5]. Three litters of water per day are required for human body, approximately 30-300 liters per person are required for domestic use which reveals water requirement for agriculture is more as compared with human needs (FAO, 2003c) [6].

Agriculture is the backbone of Pakistan's economy, according to 2013-2014 economic survey agriculture generates 21% of total output of GDP. The livelihood of more than 67% of the country's population is linked with agriculture (Arif. M, 2004) [7]. Pakistan's water resources are under stress due to large extent of agriculture activities. To meet the crop water require-

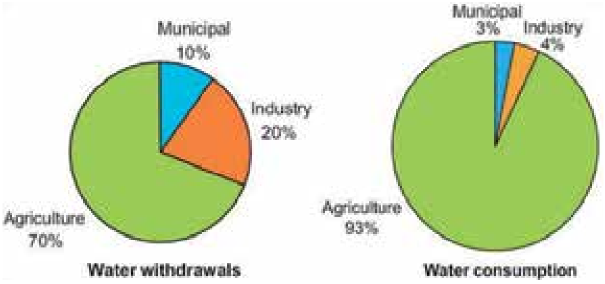

**Figure 1.** Water Withdrawals and Consumption (FAO, 2004)

ments scientific use of water resources is strongly needed. The present study was carried out on watersheds of Rawal Dam and Simly Dam located in Margalla hills, Pakistan. Both of these dams are the main source of municipal and irrigation water for Rawalpindi and Islamabad areas. The actual storage capacity of Rawal Dam was 47230 acre-feet when developed and its present storage capacity is 31000 acre-feet. Similarly the actual storage capacity of Simly Dam was 33000 acre-feet when developed and its present storage capacity is 32219 acre-feet.

## 2. Methodology

### 2.1. Study area

The study area comprises Rawal and Simly Dams located in Islamabad, the capital of Pakistan. The catchment areas of Rawal and Simly Dams are adjacent and located in Murree Hills. The Rawal Dam is located in Park area of Islamabad and Simly Dam is located 30 km east of Islamabad. The location map of the study area is given in Figure 2.

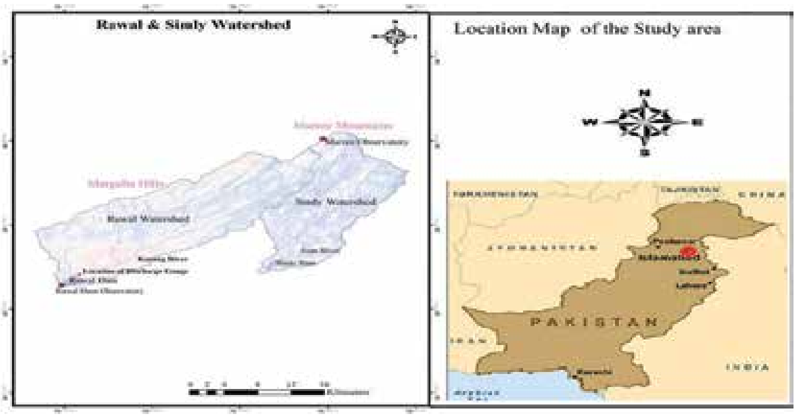

**Figure 2.** Location Map of Study Area (Landsat 2010).

The catchment areas of Rawal Dam and Simly Dam are contiguous and co-located as shown in Figure 2. The location of installed metrological stations i.e. Rawal Dam observatory and Murree observatory is also shown in Figure 2. The location map of Rawal Dam and Simly Dam is shown in Figure 3 and salient features of Rawal and Simly Dams are given in Table 1 and Table 2 respectively.

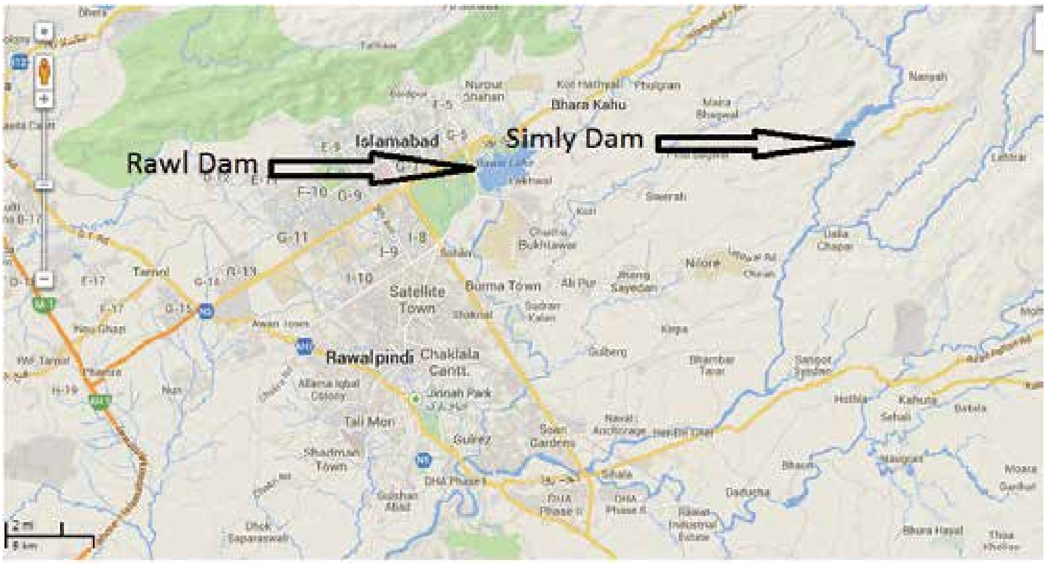

**Figure 3.** Location Map of Rawal Dam and Simly Dam.

| Name of Dam | Rawal Dam |
|---|---|
| Location of Dam | Longitude 73°-7' E , Latitude 33°-41' N |
| Constructed in | 1962 |
| Name of River | Korang River |
| Catchment Area | 106.25 sq. miles |
| Length of dam | 700 ft. |
| Spillway discharge capacity | 82,000 cusecs |
| Water supply | 14 million gallons per day |
| Right bank canal | Capacity72 cusecs.<br>Length 5 miles.<br>Cultivable commanded area 50,101 acres. |
| Left bank canal | Capacity40 cusecs.<br>Length 5 miles.<br>Cultivable commanded area 3,380 acres |

**Table 1.** Salient Features of Rawal Dam

| **Name of Dam** | **Simly Dam** |
|---|---|
| Location of Dam | Longitude 73°-20' E , Latitude 33°-43' N |
| Constructed in | 1982 |
| Name of River | Soan River |
| Catchment Area | 59 sq. miles |
| Water Supply Tunnel Length | 590 ft. |
| Spillway discharge capacity | 80,800 cusecs |
| Water supply | 47 million gallons per day |

**Table 2.** Salient Features of Simly Dam

### 2.2. Meteorological conditions

The climate of study area can be divided into four seasons as are experienced over the whole of Pakistan. These are the winter monsoon (December-February), the hot weather (March-May), the summer monsoon (June-September) and the transition period (October-November). It is summer monsoon rainstorms that give rise to the major floods. In study area Average Annual Precipitation is 1817mm, Average Annual Humidity is 61.90%, Average Annual Maximum Temperature is 16.90 °C and Average Annual Minimum Temperature is 8.7 °C (Pakistan Metrological Department).

### 2.3. Data collection

Rainfall data of Rawal and Simly catchment for the period 1975-2012 and 1983-2012 were respectively collected from Pakistan Metrological Department (PMD). The discharge data of Rawal Dam for the period 1975-2012 and Simly Dam for the period 1983-2012 were collected from Small Dams Organization Punjab and Capital Development Authority (CDA) respectively. The sediment data of Rawal catchment for the period 1975-2005 and sediment data of Simly catchment for period 1983-2008 were collected from Small Dams Organization Punjab and Capital Development Authority respectively. The temperature data of both catchments for the period 1975-2012 were collected from Pakistan Metrological Department.

### 2.4. Double mass curve

A Double Mass Curve is defined as the plot of cumulative value of one variable against the cumulative value of other quantity while the time period should be the same. The slope of the line will show the constant of proportionality between two quantities and the break in the slope of line will show the change in the proportionality constant between quantities. The Double Mass Curve can give us the significant information about the time in which changes occurred in those variables for which Double Mass Curve is plotted (Searcy and Hardison,

1960) [8]. The aim of this curve is to check the data consistency with respect to time and to detect the changes in trends by changes in the slope (Chow, 1964) [9]. (Kosmas, et al. 1997) [10], (Shahid. M, et al. 2014) [11] used Double Mass Curve for Hydrological studies. The Figure 4 is an example of double mass curve. The break in slope can be clearly observed from this figure.

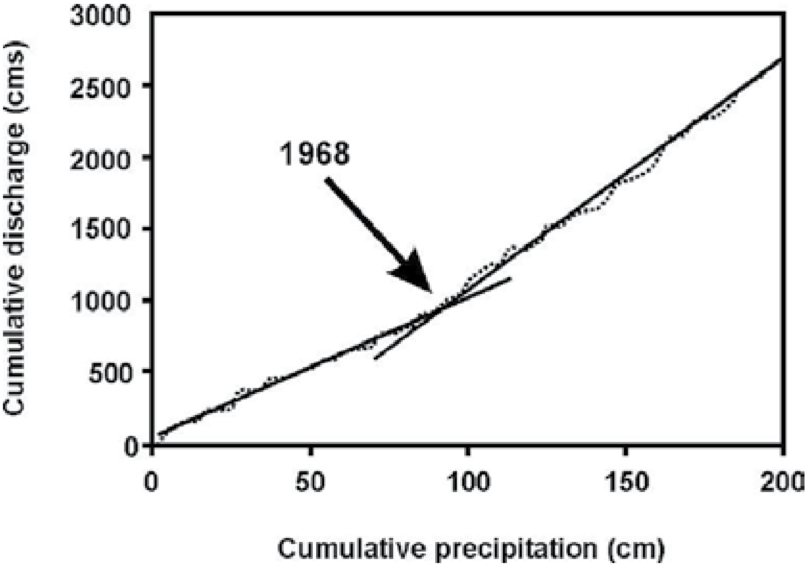

**Figure 4.** Example of Double Mass Curve Analysis.

## 3. Data analysis

### 3.1. Rainfall-Runoff relationship of Rawal catchment

The Hydrology of a region is controlled by precipitation. The annual rainfall and runoff relationship for Rawal catchment is shown in Figure 5. It can be observed in rainfall-runoff relationship of Rawal catchment that with the increase of rainfall runoff is also increasing. Annual Double Mass Curves of rainfall-runoff were plotted for Rawal catchment which are shown in Figure 6 and Figure 7. These figures show that runoff is increasing with the increase in rainfall. Figure 7 shows the Double Mass Curve and slope trend curves of Rawal catchment for 1975-1994 and 1995-2012. It is clear that for 1995-2012 slope trend curves are greater, which reveals that runoff is increasing during 1995-2012.

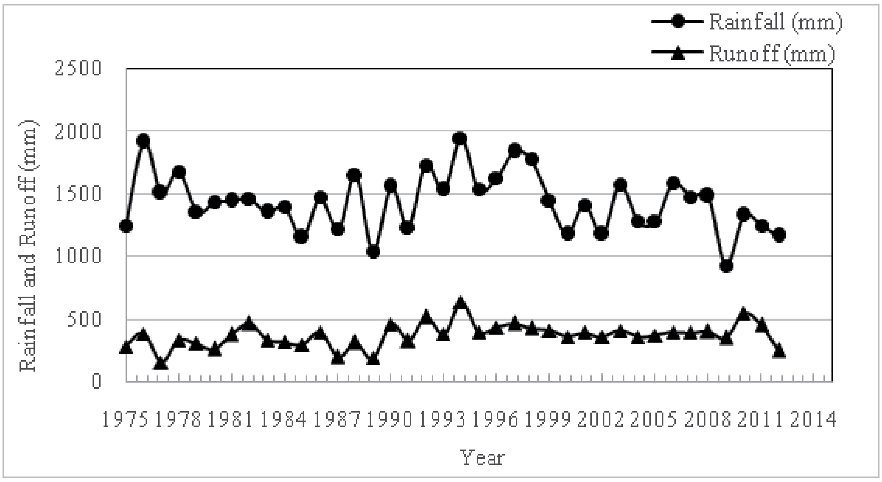

**Figure 5.** Annual Rainfall-Runoff Relationship of Rawal Catchment.

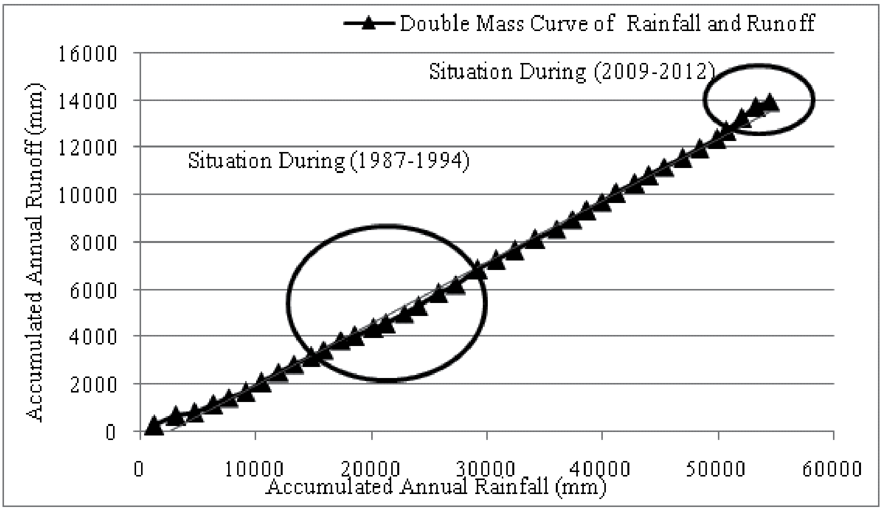

**Figure 6.** Annual Double Mass Curve of Rawal catchment (1975-2012).

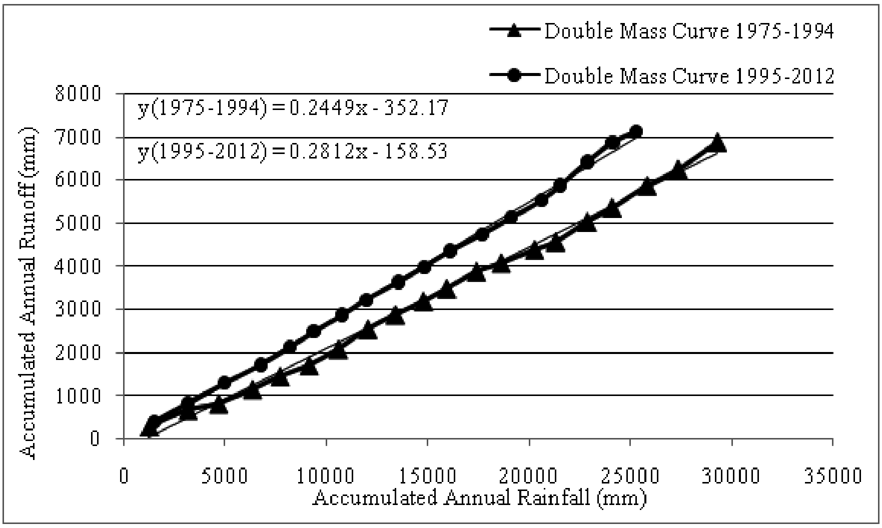

**Figure 7.** Rawal catchment Rainfall-Runoff Double Mass Curve (1975-1994) & (1995-2012).

### 3.2. Runoff-Sediment relationship of Rawal catchment

Rawal catchment runoff-sedimentation relationship using relevant organization data is given in Figure 8 and its Double Mass Curve is given in Figure 9. It is clear from Figure 8 that sedimentation rate is increasing with the increase in runoff and in double mass curve the value of slope is greater during period 1995-2005 which reveals that sedimentation is increasing with increase in runoff.

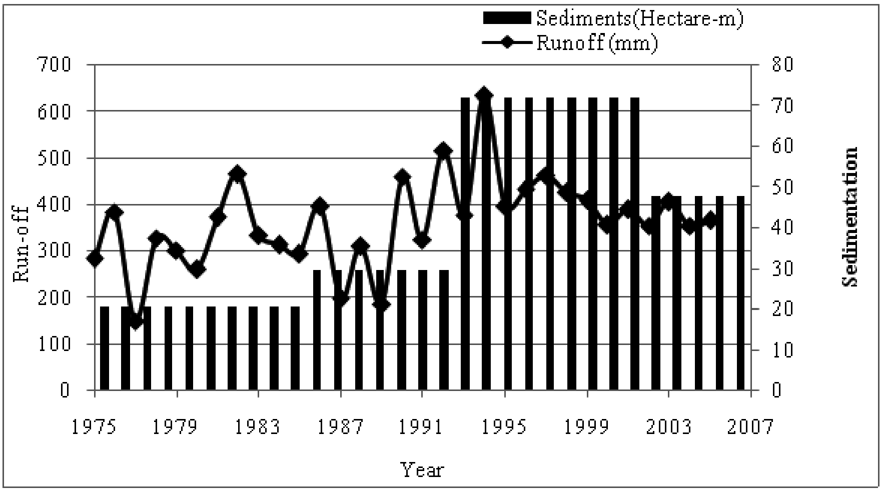

**Figure 8.** Runoff-Sediment Relationship for Rawal Catchment (1975-2005).

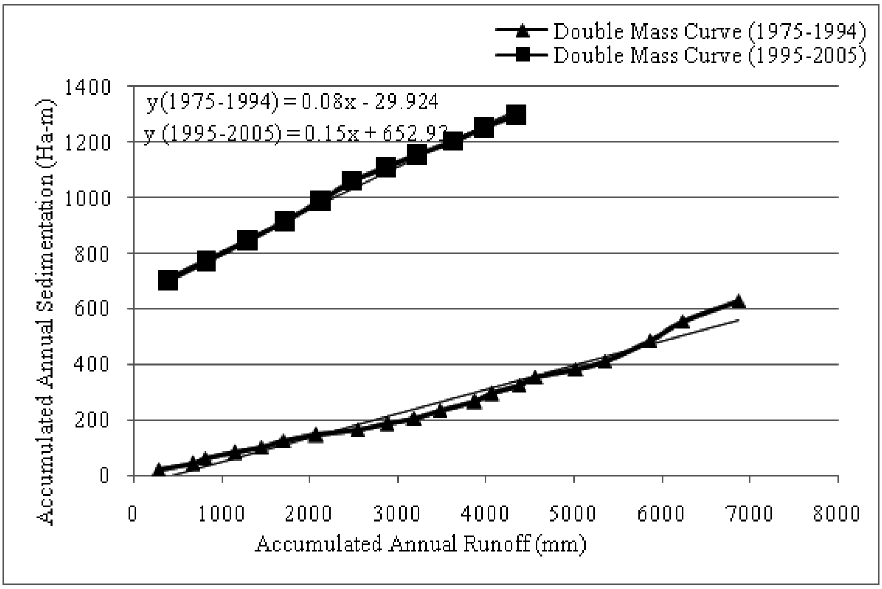

**Figure 9.** Rawal catchment Runoff-Sediment Double Mass Curve (1975-1994) & (1995-2005).

### 3.3. Rainfall-Runoff relationship of Simly catchment

The annual rainfall and runoff relationship for Simly catchment is shown in Figure 10. It can be observed in rainfall-runoff relationship of Simly catchment from 1995-2012 there is an increase in runoff from almost the same amount of rainfall which emphasize the fact that runoff amount has increased due to land use change.

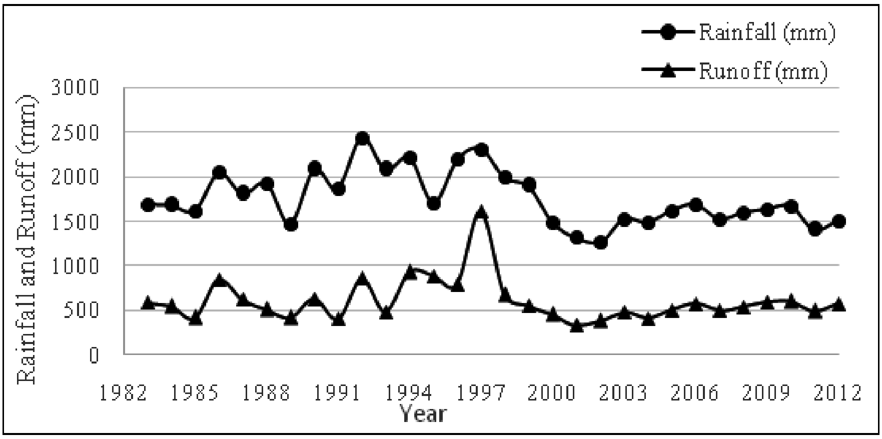

**Figure 10.** Annual Rainfall-Runoff Relationship of Simly Catchment.

Annual Double Mass Curves of rainfall-runoff were plotted for Simly catchment which are shown in Figure 11 and Figure 12. These figures show that runoff is increasing with the increase in rainfall. It is clear from the Figure 11 that with the increase in rainfall runoff is also increasing. Figure 12 shows the Double Mass Curve and Slope Trend Curves of Simly catchment for 1983-1994 and 1995-2012. It is clear from Figure 12 that slope trend curves and values of slopes from regression coefficients are greater during 1995-2012 which reveals that runoff is increasing during 1995-2012.

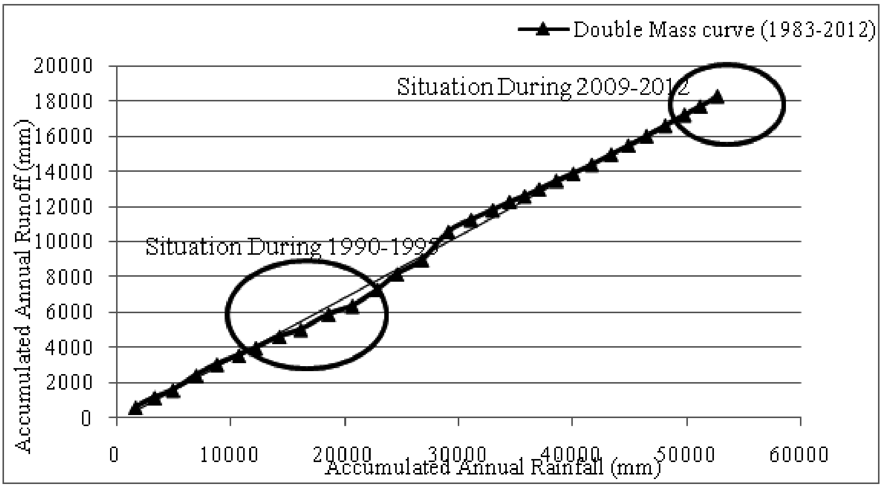

**Figure 11.** Annual Double Mass Curve of Simly catchment (1983-2012).

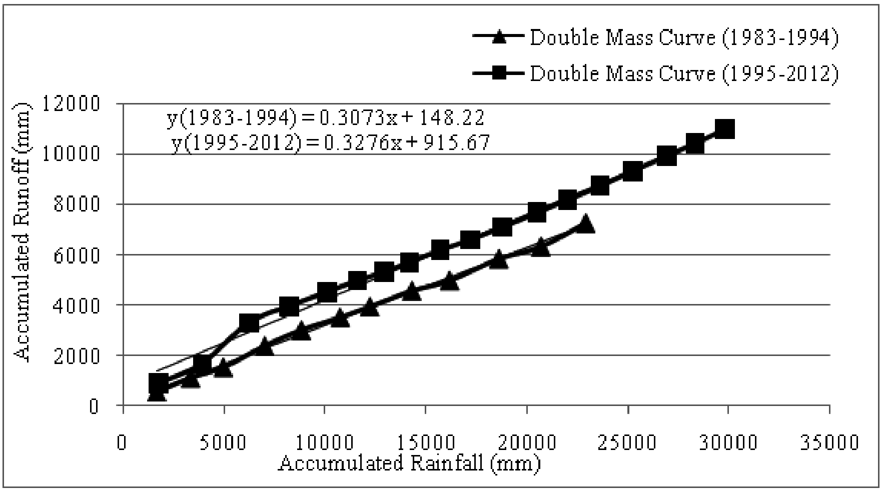

**Figure 12.** Simly catchment Rainfall-Runoff Double Mass Curve (1983-1994) & (1995-2012).

### 3.4. Runoff-Sediment relationship of Simly catchment

Simly catchment runoff-sedimentation relationship using relevant organization data is given in Figure 13 and its Double Mass Curve is given in Figure 14. It is clear from Figure 13 that during1995-2005 more sedimentation occurred as compared with sedimentation during 1982-1994. Figure 14 is Double Mass Curve which shows the value of slope is greater during period 1995-2012 which reveals that more sedimentation occurred during 1995-2012.

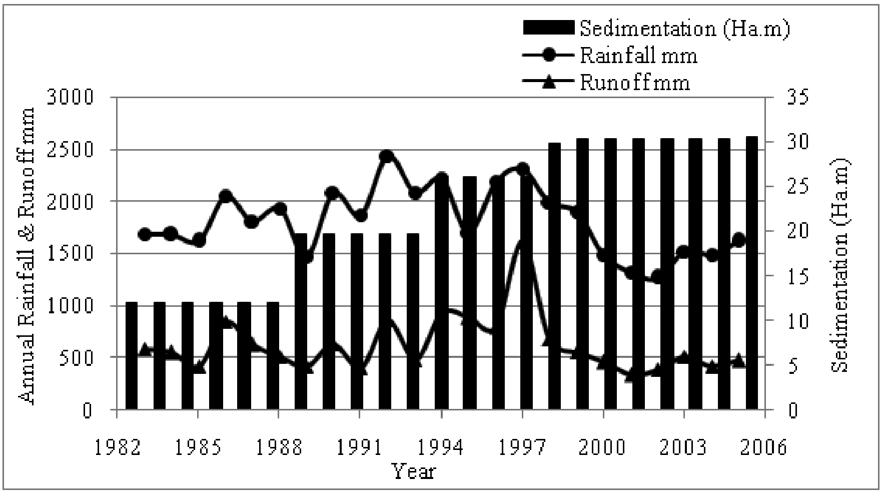

**Figure 13.** Runoff-Sediment Relationship for Simly Catchment (1983-2012).

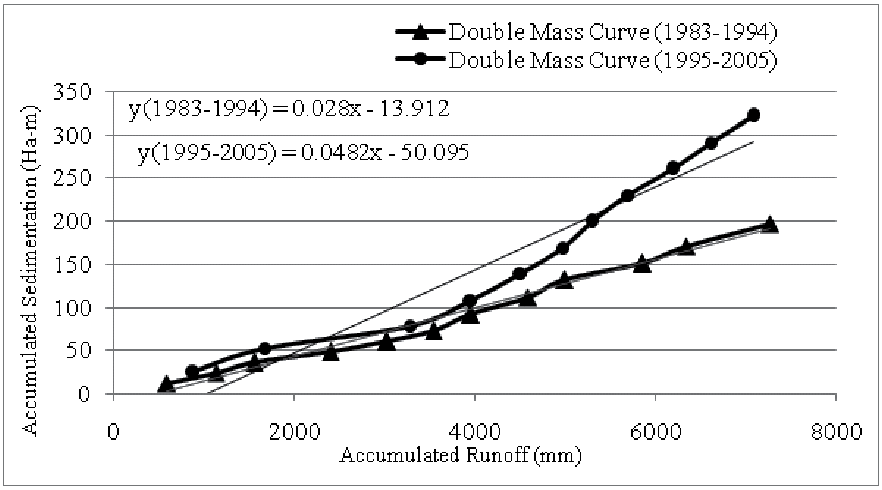

**Figure 14.** Simly catchment Runoff-Sediment Double Mass Curve (1975-1994) & (1995-2012).

### 3.5. Methods practiced for irrigation in study area

In Rawalpindi out of 25,000 acres an area of 820 acres are irrigated from Rawal dam and 16000 acres are irrigated by tube wells. Similarly 35 acres nurseries of CDA and private farms are irrigated from Simly Dam. The crops cultivated in study area are wheat, corn, maize and rice. Currently the surface (flood) irrigation methods are being used to irrigate the fields. Flood irrigation method is one of the oldest and obsolete methods for irrigation. In flood irrigation method a field is essentially flooded with water where the water submerges the soil. In flood irrigation too much care is required to avoid water losses. In flood irrigation water losses are more mostly due to seepage, runoff, deep percolation and evaporation. The flood irrigation is shown in Figure15.

**Figure 15.** Flood Irrigation Method.

The flood irrigation method is least efficient method and its efficiency is between 40-70% (Gill. A.M, 2010) [12]. Even the fruit orchards and vegetable gardens are being irrigated on the same pattern and methodology. The surface irrigation techniques (furrow, strip or basin) are really not beneficial to the crop productivity but their poor performance often results in wastage of water and at times in excessive water application. This also causes the root decay and decline in crop productivity.

In the current irrigation practices the water regulation is least under the control of the farmer. Water is applied when it is available with disregard to the crop demand and other hydrological and metrological inputs. In addition to all of this, losses due to evaporation also put a lot of stress on the system.

More regulated and controllable irrigation systems like sprinkler and drip irrigation systems are difficult to install and may not be initially viable because of exhaustive costs. However these have proved to be more efficient in water management and financially beneficial over life cycle cost analysis. A comparison of various water management practices and system efficiencies is given in Figure 16.

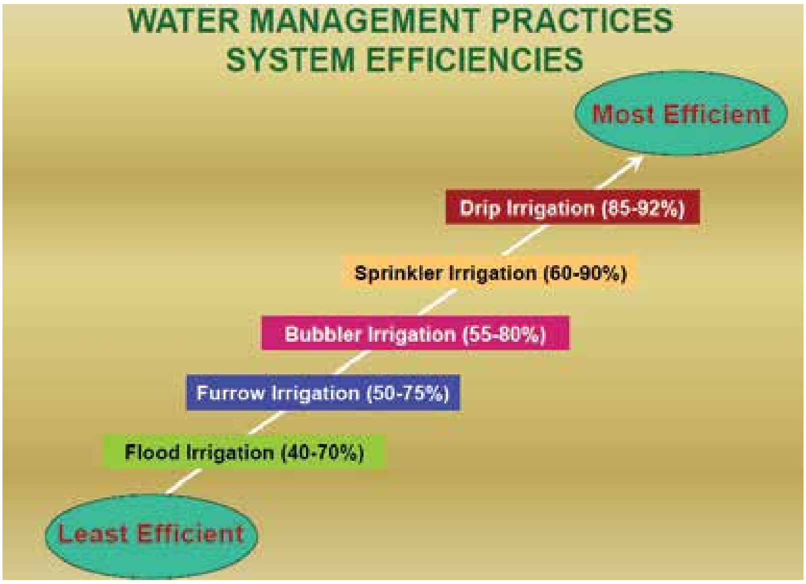

**Figure 16.** Water Management Efficiencies.

From Figure 16 it is clear that Drip irrigation method is most efficient. By remodeling of Rawal Dam and Simly Dam their storage capacity can be increased and by lining of the Rawal Dam Left Bank Canal seepage losses can be reduced thus increasing the velocity of water which will increase the efficiency of drip irrigation system whenever installed.

## 4. Conclusions

**a.** From Double Mass Curve analysis it can be concluded that during 1995-2012 the slope trend curves were more which shows in both Rawal and Simly Dam catchment runoff increased with the time.

**b.** Double Mass Curve analysis showed that in Both Rawal and Simly Dam catchment sedimentation increased with the time as the slope trend curves were more during 1995-2005 which shows more sedimentation occurred in both catchment during 1995-2005.

**c.** Due to increase in runoff, sedimentation increased in both catchments thus reducing the storage capacity of both dams.

**d.** The irrigation methods practiced in study area are least efficient and mostly water losses are due to obsolete irrigation methods.

## 5. Recommendations

**a.** In study area mostly water losses are due to seepage and evaporation. The lining of canals will reduce seepage loses and it will increase velocity of water so canal lining is strongly recommended.

**b.** The irrigation methods practiced in the study area are old and obsolete. To achieve a better efficiency it is strongly recommended that for irrigating the fields and orchards, drip irrigation method should be installed in the study area.

**c.** The increase in runoff and sedimentation may be due to land use changes in the catchment areas. It is strongly recommended to evaluate the impact of land use changes in both Simly and Rawal catchments.

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Chapter 5

# Water Balance of Flooded Rice in the Tropics

Siva Sivapalan

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/59043

## 1. Introduction

### 1.1. Rice as a world food

The world human population has been estimated at 7.2 billion in mid-2013 and is projected to reach 9.6 billion by 2050 [1]. There is an urgent need for current world food production levels to substantially be increased in order to avoid hunger and starvation of ever increasing human population. Rice and wheat are important sources of food for people around the world. Moreover, rice is considered as a staple food for about half of the world's population [2]. More than 56-61 per cent of the world's population lives in the Asian Region and the Asian population is growing at 1.8 per cent per year which adds 45-51 million more rice consumers annually [3,4]. Over 90 per cent of the world's rice is produced and consumed in the Asian Region by countries such as China, India, Indonesia, Bangladesh, Vietnam and Japan [4]. It has been estimated that rice production has to be raised by at least 70 per cent over the next three decades to meet the growing demands [5]. The demand for rice and its value-added products is growing steadily, with consumption stretching beyond Asia. For example, annual rice consumption in Australia increased from approximately 5 kg/capita to 10 kg/capita during the past nine years [6].

World rice production in 2013 accounts for 496.6 million tonnes of milled rice and only 37.3 million tonnes (i.e. 7.5% of total production) was traded between countries [7]. Australia produced 1.16 million tonnes of paddy rice in 2013 and usually exports 85% of its rice production to more than 60 countries around the world [8]. Irrigated rice in the world accounts for 79 million hectares (55% of the global harvested rice area) and contributes 75% of global rice production [9]. To keep pace with population growth, rice yields in the irrigated environments must increase by 25% over the next 20 years [9]. Irrigation is the main water source in the dry season and is used to supplement rainfall in the wet season. Inefficient use of irrigation water is one of the main agronomic problems encountered where intensive rice cultivation is practiced.

### 1.2. Features of tropical regions

Most of the world's rice is grown in the tropics. The tropical region comprises the area between the Tropic of Cancer (23°27'N latitude) and the Tropic of Capricorn (23°27'S latitude). This region experiences tropical climate which is usually marked by hot and humid weather conditions. Vast amount of sunshine along with extremely heavy rainfall is the distinct feature of this climate. The season is marked with two wet and two dry seasons in areas close to equator. Further away from the equator, the climate becomes as monsoonal which has one wet season and one dry season. Wet seasons in the Northern Hemisphere occur during May to July and in the Southern Hemisphere during November to February [10].

The tropical regions of Australia are in the north of the country and include the equatorial and sub-tropical zones (Figure 1) which experience hot temperatures and very high relative humidity values. The wet season which is sometimes referred as the monsoon season starts in November and finishes in March next year. It is usually hot where the temperature varies between 30 and 50 degrees Celsius. Large amounts of water vapour in the atmosphere create high humidity during the wet season. Frequent flooding may occur due to heavy rain events during the wet season. The dry season starts in April and finishes in October. Low temperatures and clear skies are the main characteristics during the dry season. Average temperature in the dry season is about 20 degrees Celsius [11].

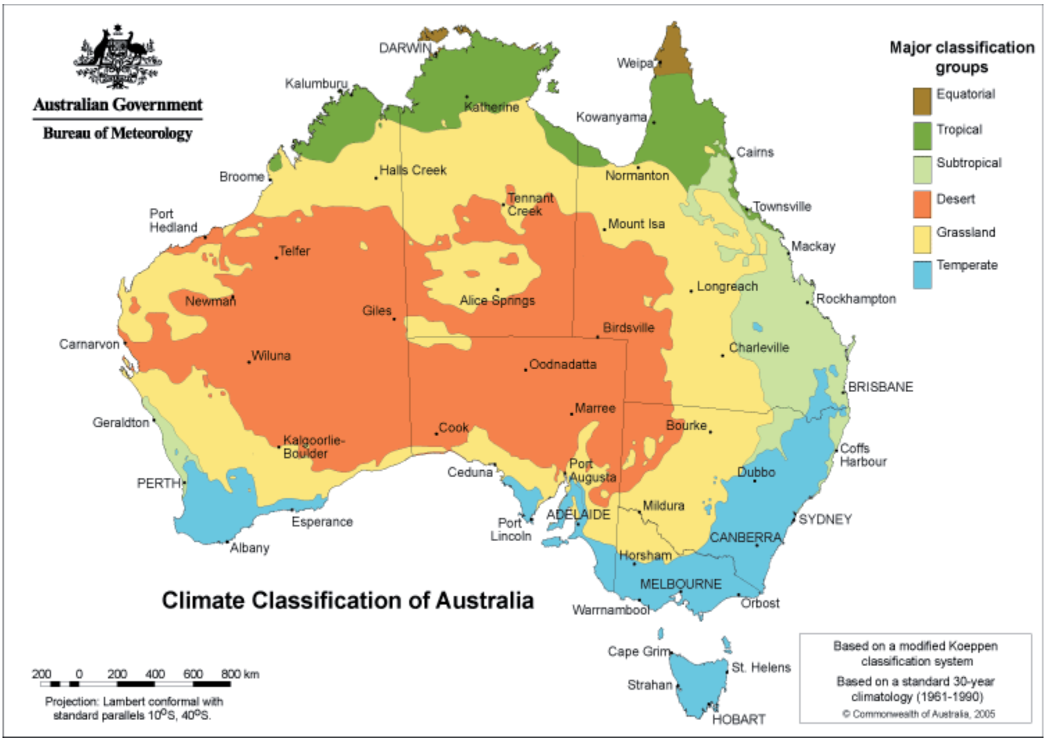

**Figure 1.** Tropical regions of Australia. Source: [12].

The tropical region in Australia covers 5 to 17 million hectares of arable soil. It is important to realise that the run-off from this region is roughly 152,000 GL and less than 6 per cent of this run-off is currently being used. In contrast, the total amount of water used for agriculture in the whole country is about 12,200 GL [13]. Therefore, it is predicted that by increasing the usage of available water resource in the tropical regions of northern Australia, it would be possible to double Australian agricultural output and make a significant contribution towards combating global hunger and supporting food security [13]. For example, suitable soil types, a warmer climate, and availability of irrigation water make the Ord River Irrigation Area in north-eastern Western Australia ideal for growing rice. Potential yields up to 14.3 t/ha have been demonstrated in this environment [14].

### 1.3. Rice cultivation

Rice belongs to the family *Gramineae* and genus *Oryza*. The genus *Oryza* comprises about twenty species distributed through tropical and subtropical regions of Asia, Africa, Central and South America and Australia. There are only two species of cultivated rice, *O.sativa* and *O.glaberrima*. *O.sativa* is a common rice widely grown in the tropical and temperate zones, and *O.glaberrima* is endemic to West Africa. Cultivars of *O.sativa* are divisible into three types or races: *Indica*, an elongated, thin and slightly flattened grain which stays separate in cooking; *Japonica*, a broad, thick, short, rounded grain which tends to soften if over-cooked; and *Javanica*, a long and sticky variety which possibly originated in Indonesia.

Rice is a remarkable semi-aquatic plant which has been cultivated for at least 8,000 years in widely different agro-climatic regions of the world. *O.sativa* grows at latitudes from 36° south in Australia to 49° north in Czechoslovakia at altitudes from sea-level to 2,400 metres in Kashmir. *O.sativa* is grown extensively in tropical and temperate regions, normally in water (lowland) but also as a dry-land (upland) crop. It is believed that rice cultivation must have begun at several different locations in Asia between 7,000 and 8,500 years before present time. *O.sativa* probably spread from India to Egypt, Europe, Africa, the Americas and Australia in that order.

First likely introduction of rice seed into southern Australian gold fields was by Chinese prospectors in the 1850s cultivating it in marshy areas or in ponds using effluent from mining. In the 1860s, a small rice industry using upland varieties and Chinese labour emerged in the northern Queensland to supply local demand in the North Queensland gold fields. In 1906, a Japanese ex-parliamentarian, Isaburo (Jo) Takasuka, began cultivating rice using Japanese (Japonica) varieties near Swan Hill in Victoria. In 1924, a commercial rice industry began around Leeton and Griffith in New South Wales.

### 1.4. Water management of rice

Rice requires more water than most other crops. Most rice varieties achieve better growth and produce higher yields when they are grown under flooded conditions than under aerobic conditions. In addition, the ponded water helps to suppress the weeds, especially broadleaf types. The ponded water provides protection against low night time air temperatures at some locations where the problem of cold damage to crop exists [15,16]. Paddy rice is usually grown in level basins which are flooded with water throughout most of the growing season. In general, areas of irrigated agriculture are prone to rising groundwater, waterlogging and salinity under poor irrigation practices when excess groundwater recharge rates occur. Under extreme circumstances, these negative effects may lead to loss of arable land and/or create additional crop or land management practices for which the grower may need to cover the extra costs. It is believed that flooded rice systems may have contributed to excess groundwater recharge rates at some locations [17,18].

It has been estimated that up to 62% of the world population will be facing water scarcity by 2030 [19]. Currently, there are many countries experiencing water scarcity for food production, for example, China [20]. Hence water will be a major constraint for agriculture in coming decades. The actual water availability in Asia, for example, decreased from 9.6 ML/year.capita in 1950 to 3.37 ML/year.capita in 1990, due to the increase in population [21]. In Asia, about 90% of fresh water diverted from water resources is used for agricultural purposes and more than 50% of this water is used to irrigate rice [22]. World population increase will likely further reduce the availability of water per capita in many countries. Hence, an appropriate response to water scarcity is to focus on the improvement of the overall productivity of water (i.e. the output of goods and services in physical or monetary terms per unit of water applied or consumed) to feed an ever-increasing world population.

With increasing water scarcity for irrigation, productivity of current rice production systems has to be improved substantially. Attempts have already been made at the International Rice Research Institute in Philippines to improve the water productivity of irrigated rice-based systems in Asia [23,24]. Modern rice varieties and advanced water management techniques warrant new estimations of water losses from flooded rice crops. This study reports on a water balance approach taken to determine the evaporation, transpiration and deep percolation losses from flooded rice bays in a tropical environment using a set of lysimeters and lock-up bay tests. Deep percolation under ponded rice culture should be within acceptable leakage rates and should not unduly affect growers or environmental managers in terms of rising groundwater levels, waterlogging and salinity.

### 1.5. Water balance of rice fields

The term 'water balance' refers to the accounting of water going into and out of an area. The quantity of water added to, subtracted from, and stored within a set volume of soil during a given period of time is considered. It is assumed that in a given volume of soil, the difference between the amount of water added $W_{in}$ to the soil and the amount of water removed $W_{out}$ from the soil during a certain period is equal to the change in soil water content $\Delta W$ during the same period of time [25]:

$$\Delta W = W_{in} - W_{out} \tag{1}$$

For this study, it is most appropriate to consider the water balance of the root zone per unit area of field. Thus the root zone water balance is expressed as [25]:

$$(\Delta S + \Delta V) = (RF + IR + UP) - (RO + DP + E + T) \tag{2}$$

where

$\Delta S$ is change in root zone soil moisture storage

$\Delta V$ is increment of water incorporated in the plants

$RF$ is rainfall

$IR$ is irrigation water

$UP$ is upward capillary flow into the root zone

$RO$ is runoff

$DP$ is downward drainage out of the root zone

$E$ is direct evaporation from the soil/water surface

$T$ is transpiration by plants

All quantities in Equation (2) are expressed in terms of volume of water per unit area of soil (that is equivalent depth units) during the period considered. Thus the components of the water balance equation are expressed in units of water depth (mm), assumed to be spread uniformly across the paddock:

$$1\text{ mm on 1 hectare} = 10\text{ m}^3 = 10{,}000\text{ L} = 0.01\text{ ML} \tag{3}$$

The various items entering into the water balance of a hypothetical rooting zone for a flooded rice system are illustrated in Figure 2. The principal moisture losses from the rice paddy may be grouped into vapour losses and losses in liquid form. The vapour losses are loss by transpiration from the leaf surface and by evaporation at the water surface. The liquid losses are the downward movement or vertical percolation of free water and the runoff of excess water over the field levees. The combined losses of water resulting from plant transpiration and surface evaporation are called evapotranspiration (ET). It is also commonly referred to as consumptive water use. The ET rate is affected by solar energy, temperature, wind or air movement, relative humidity, plant characteristics and soil water regime [26].

A direct method for measuring field water balance is using a set of lysimeters. A lysimeter is a container filled with soil and installed in the field so that it will represent the prevailing soil and climatic conditions. It allows accurate measurement of certain physical processes occurring in the field. In terms of the field water balance, these lysimeters allow continuous measurement of both evapotranspiration and percolation. The change in water level in square or circular tank lysimeters is measured to refer to evapotranspiration [27,28].

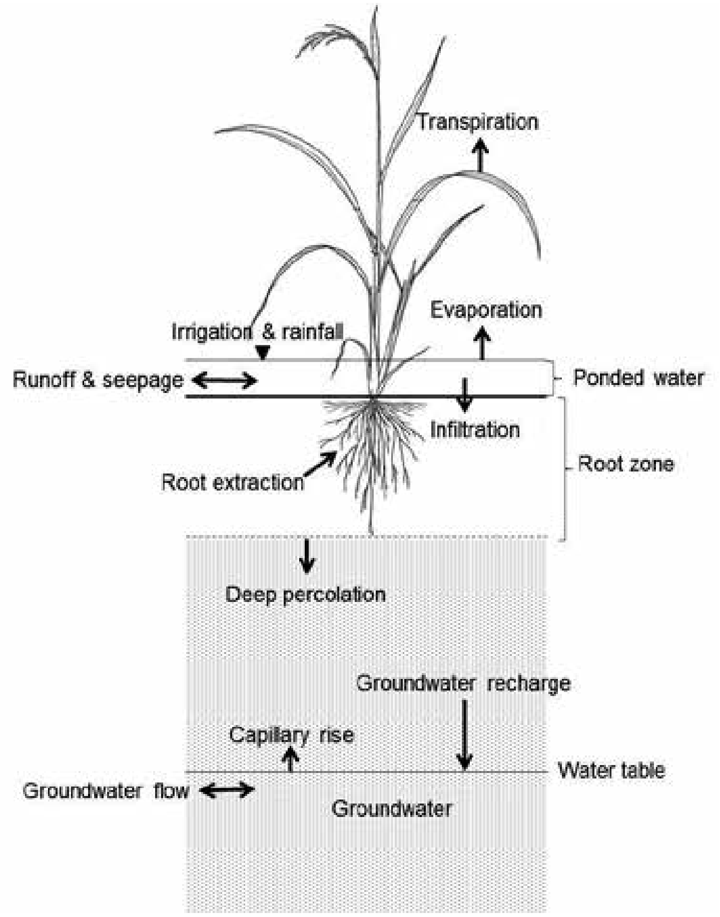

**Figure 2.** Schematic representation of the water balance of a flooded rice field.

## 2. Materials and methods

### 2.1. Site description

The study was conducted at a site (15.65ºS latitude, 128.72ºE longitude, 31 m altitude), located within the research facility of the Frank Wise Institute of Tropical Agriculture in Kununurra in Western Australia. The Frank Wise Institute of Tropical Agriculture is the regional office of the Department of Agriculture and Food, Western Australia (DAFWA) to provide service to the local growers in the Ord River Irrigation Area (ORIA) to improve their farming business. The study site is located within a region which has a tropical monsoonal climate and most of the mean annual rainfall (about 825 mm) occurs during the period from October to April (Table 1). The warm climate (average annual maximum temperature is 35ºC) of the region enables rice to be grown twice (during the wet and the dry seasons) in a year. In addition, it is possible that the monsoonal rains during the period from November to March can provide more than half of the water required for a wet season rice crop. Since cloud cover can reduce the sunshine hours during the wet season, this might be a hindrance to achieve high rice yields. In addition, high humidity experienced during the wet season might favour the occurrence of certain pests and diseases (for example, the devastating rice blast disease).

| Month | Air temp min(°C) | Air temp max(°C) | Humidity average (%) | Rain (mm) | Total solar (kJ/m$^2$) | Wind max (km/h) |
|---|---|---|---|---|---|---|
| January | 21.6 | 41.0 | 70.2 | 91.2 | 806586.6 | 52.56 E |
| February | 22.8 | 41.3 | 75.2 | 146.4 | 666768.2 | 35.64 WSW |
| March | 20.4 | 39.1 | 75.1 | 67.4 | 724862.3 | 43.56 ENE |
| April | 12.8 | 38.7 | 67.4 | 89.6 | 685514.2 | 25.56 NNE |
| May | 9.9 | 37.8 | 61.5 | 5.0 | 609878.9 | 34.56 NNE |
| June | 8.9 | 35.3 | 54.9 | 3.0 | 605294.8 | 32.76 SSW |
| July | 3.9 | 35.4 | 47.1 | 0.0 | 708597.7 | 25.20 SE |
| August | 4.7 | 37.7 | 50.2 | 0.0 | 813523.3 | 29.16 ESE |
| September | 14.0 | 40.5 | 54.3 | 0.0 | 814916.5 | 38.52 ESE |
| October | 14.6 | 42.4 | 52.2 | 23.4 | 829273.6 | 47.88 NW |
| November | 18.1 | 42.4 | 61.2 | 111.4 | 792809.0 | 48.60 NE |
| December | 22.8 | 40.9 | 72.8 | 192.2 | 712451.7 | 48.60 NNE |

**Table 1.** Local weather data from a meteorological station located near the study area during 2013 (source: [29]).

## 2.2. Soil characteristics

The study was conducted on Cununurra clay soil which is the major soil type in the region. This soil is classified as the great soil group of the Grey, Brown and Red Clays of Stace et al. [30]. It belongs to fine montmorillonitic typic chromo usterts in Soil Taxonomy (USDA) and Ug5 class of Northcote [31]. Typical Australian Soil Classification (ASC) for this soil type is self-mulching Vertosol [32]. The Cununurra clays could be referred as black soils, black earths or gilgai soils. These soils occur on the black soil plains. These soils were derived from parent materials formed by Riverine deposits. Typical soil profile description of Cununurra clay is given in Table 2 where relationship between approximate field texture and clay content is for loams 20%, clay loams 30%, light clays 40%, medium clays 50%, medium heavy clays 60%, and heavy clays 70% [33].

| Horizon | Depth | Characteristics |
|---|---|---|
| A-11 | 0-5 cm | Very dark greyish-brown (2.5Y 3/2); light to medium clay; dry and loose (self-mulching); granular structure; smooth-ped to rough-ped fabric; and pH 7.5. |
| A-12 | 5-25 cm | Very dark greyish-brown (2.5Y 3/2); medium to heavy clay; dry and extremely firm; medium blocky structure; smooth-ped fabric; pH 8.0; traces of carbonate nodules; some manganiferous concretions; some indistinct slickensides; shrinkage cracks very evident; and peds approximately 4 × 8 cm. |
| A-13 | 25-125 cm | Very dark greyish-brown (2.5Y 3/2); heavy clay; dry and extremely firm; coarse blocky structure evident in the drier parts with prismatic peds 15 × 30 cm; smooth-ped fabric; pH 8.5; traces of carbonate nodules; some manganiferous concentrations; some lenses of fine sand; and shrinkage cracks sometimes penetrate the top of this horizon. |
| AC-1 | 125-140 cm | Dark brown (10YR 3/3, 7.5YR 3/2); medium to heavy clay; slightly moist and extremely firm; smooth-ped fabric; pH 8.6; 2-5% carbonate nodules; traces of manganese concretions; some weakly bound concretions of soil material and inclusions of AC-2 horizon material. |
| AC-2 | More than 140 cm | Dark reddish brown (5YR 3/4); medium clay; slightly moist and very firm; pH 8.5; up to 5% large carbonate nodules; smooth-ped faces evident but fabric may be earthy; and increasing micaceous material. |

**Table 2.** Soil profile description of Cununurra clay (source [34]; Copyright © Western Australian Agriculture Authority).

The most important characteristic common to all swelling clays including the Cununurra clay is the high content of clay size particles with expanding clay minerals such as montmorillonite. Cununurra clays are referred to as self-mulching due to formation of a thin surface layer consisting loose dry granules after repeated wetting and drying cycles [35]. Tillage is often very difficult on these heavy clays. The optimum moisture range for tillage is narrow. If the soil is too wet, moist soil will stick to implements. When the soil is too dry, it has considerable strength and will result in high implement draft, wheel slip and high fuel consumption. It will also accelerate wear on implement points and tractor tyres. These soils are normally cultivated dry to achieve a better tilth. Even a little moisture causes large clods to be turned up during ploughing. Generally, infiltration rates in swelling clay soils are low. The magnitude of subsoil conductivity is about $10^{-7}$ m/sec [34].

### 2.3. Water management

The trial was undertaken during the dry season under ponded rice culture (flooded system) covering the period from 12 June 2013 to 2 October 2013 (112 days). The crop was established by dry seeding (drill sown into cultivated seedbed) at a rate of 152 kg/ha to a depth of 2-3 cm and intermittently irrigated (flushing) twice, the first - immediately after sowing and the second - 14 days later. With intermittent flushing irrigation, the irrigation water was applied enough to cover the soil surface and quickly drained off after 2-3 hours. When the seedlings were 5-10 cm tall and at the 3-5 leaf stage, permanent water to a depth of 3-5 cm was applied, on 31 days after planting. A shallow water depth of 5-10 cm was maintained through the vegetative phase. As the crop approached the panicle initiation (PI) stage, water level was raised to 10-15 cm, and then further increased to achieve a depth of 20-25 cm at early pollen microspore (EPM) stage. Water level was raised to protect the developing panicle from cold temperatures. Once flowering commenced, the water level was allowed to drop to 5-10 cm. Water level of at least 5 cm depth was maintained through grain filling until lockup the bay for the remaining water to be used by the crop at physiological maturity.

In terms of water management of the experimental site, 'Lockup bay tests' as proposed in reference [36] were adopted. For a lockup bay test, the water flow between the bays is prevented and the change in water depth each day over a period of several days is recorded. In this trial, no inflow or outflow within the bay is maintained. This means applying water (top-up) to the paddock as required and then sealing the inlet to prevent further entry of water until the next irrigation event, usually in about 7 days. The outlet was kept sealed throughout the trial period. Since ponded rice culture was undertaken in adjacent bays in both sides, the lateral seepage from the test bay was considered minimum. Just before commencement of the experiment, the tail-end bank was sealed using a plastic barrier to prevent lateral seepage. With the application of permanent water to the crop on 10 June 2013, lockup bay tests were started and continued until the water in the bay disappeared on 2 October 2013 before harvest.

### 2.4. Setup of Lysimeters

A modified lysimeter experiment [26-28] was conducted to estimate water losses due to evaporation, transpiration and deep percolation under ponded rice culture. Three steel lysimeter rings (two with open-end and one with closed-end) were used. Each lysimeter ring was 50 cm in diameter, 70 cm in height and 5 mm wall thickness. The open-end type lysimeters were installed by pushing the cylinder vertically into the soil up to 35 cm below ground level using heavy machinery. Moist soil from previous flush irrigations made this process easy with minimum disturbance to the soil located inside and outside of the lysimeters. A 50 cm diameter and 35 cm deep hole was dug in the ground and the closed-end type lysimeter was pushed vertically into the hole. This lysimeter was filled with the same soil up to 35 cm. All three lysimeters had 35 cm of the ring protruding above the ground surface. Each lysimeter had a 10 mm diameter hole at 2 cm above ground level to facilitate entry of water into the lysimeter during irrigation events. This allowed the water level inside the lysimeter and that of the surrounding field be same at the end of irrigation. Immediately after irrigation, these holes on the lysimeters were closed using rubber stoppers and industrial lubricant. The holes were kept closed until the start of the next irrigation event when this procedure was repeated. All three lysimeters were installed in the cropped area (Figure 3) but only one open-end type lysimeter had undisturbed rice plants representative of the plants in the surrounding field. Any rice plants found in the rest of the lysimeters were removed.

**Figure 3.** Field setup of lysimeters and Class A Evaporation Pan for two planting configurations.

It was possible to measure the evaporation (E), transpiration (T) and deep percolation (DP) components by comparing losses from each lysimeter (Figure 4). During each irrigation event (i.e. topping up the bay), the side valve on each lysimeter was opened to allow water inside. Automatic water level recorders were installed in each lysimeter to monitor the water level at 30 minute intervals. Water losses were calculated within each irrigation cycle. Evaporation was the water loss measured in Lysimeter A. For comparison purposes, a Class A Pan was also installed at this site to measure the actual evaporation. Evaporation data from Lysimeter A was primarily used to separate the evaporation component from Lysimeters B and C. Transpiration was the water loss measured in Lysimeter C minus water loss measured in Lysimeter B. Deep percolation was the water loss measured in Lysimeter B minus water loss measured in Lysimeter A. In a flooded system, generally 90% of roots are located in the top 10 cm of the soil [37] and the internal drainage beyond the root zone has been referred to as deep percolation [25]. For this trial, water moving downward from open-end of the lysimeters at 35 cm depth was considered as deep percolation. A 10 cm diameter polyvinyl chloride (PVC) cylinder with a hole at ground level was also used to monitor the water level of the surrounding field. This PVC pipe allowed to remove the effect of ripples, that formed in the surrounding water in the field, on measurement of the water level by the recorder. The effect of different water levels within lysimeters compared with that of the surrounding field towards the end of the irrigation cycle, as shown in Figure 4, will be discussed later.

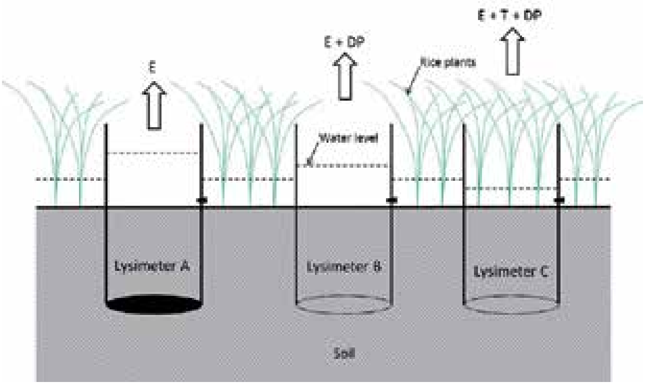

**Figure 4.** Diagram of lysimeters to measure evaporation (E), transpiration (T) and deep percolation (DP) losses in a paddy field, where the arrows indicate combined water losses.

## 2.5. Description of Class A pan

A Class A Evaporation Pan (Figure 5) was installed at the experimental site to measure the actual evaporation losses under a paddy field situation and to compare with evaporation observed in Lysimeter A described above. The pan was constructed according to FAO recommendations [38]. The Class A Evaporation pan was circular, 120.7 cm in diameter and 25 cm deep. It was made of galvanized iron (22 gauge). The pan was mounted directly on the ground surface within a cropped area and ponded water. The pan was made level before it was filled with water from the surrounding field to 5 cm below the rim. The water level was not allowed to drop to more than 7.5 cm below the rim by filling the pan whenever required. Few granules of Copper Sulphate were added to the water in the pan to prevent slime build up. The site was located within a large cropped field (Figure 3). An automatic water level recorder was used to monitor the changes in water level within the pan at 30 minute intervals. Measurements were made in a stilling well that was situated in the pan near one edge (Figure 5). The stilling well is a metal cylinder of 10 cm in diameter and 20 cm deep with a small hole at the bottom which allowed the water levels within the stilling well and the pan to remain the same. Usage of a stilling well removed the effect of ripples on measurement of the water level by the recorder. Ripples occasionally formed within the pan when the wind velocity was high.

**Figure 5.** Class A Evaporation Pan with a stilling well located near one edge (also shown is a Baro-Diver to measure variations in atmospheric pressure).

## 2.6. Automatic water level recorder

Cera-Diver® and Baro-Diver® manufactured by Schlumberger Water Services in the Netherlands were used in this study to monitor water level fluctuations in lysimeters, evaporation pan and the surrounding field. The Divers consist of a pressure sensor designed to measure air/water pressure, a temperature sensor, memory for storing measurements and a battery. Both Cera-Diver and Baro-Diver measure the absolute pressure and temperature. Note that the absolute pressure is the pressure of the water column above the Diver plus the atmospheric pressure. Therefore measurement of atmospheric pressure is required to determine the water level. Cera-Divers establish the height of a water column by measuring the water pressure using the built-in pressure sensor. The height of the water column above the Diver's pressure sensor (Figure 6) is determined on the basis of the measured pressure. Baro-Diver measures atmospheric pressure and is used to compensate for the variations in atmospheric pressure measured by the Cera-Divers. To measure the variations in atmospheric pressure, a Baro-Diver was installed at the experimental site (Figure 5).

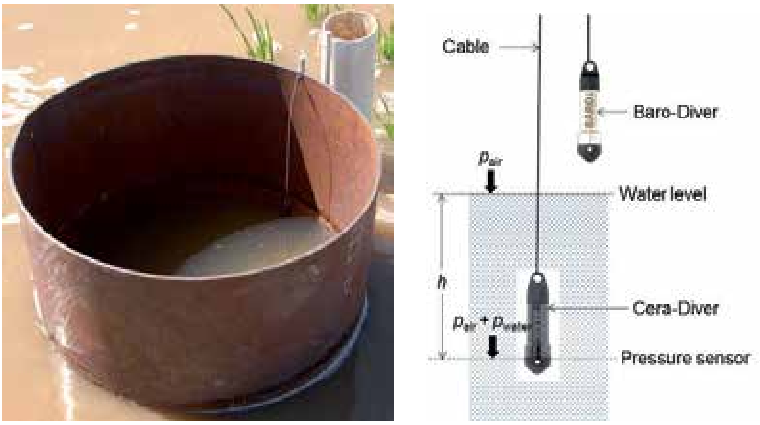

**Figure 6.** Installation of a Cera-Diver to measure the height of water.

The Baro-Diver measures the atmospheric pressure ($p_{air}$) and the Cera-Diver measures the pressure exerted by the water column ($p_{water}$) and the atmospheric pressure ($p_{air}$). Thus

$$p_{Baro-Diver} = p_{air} \tag{4}$$

and

$$p_{Cera-Diver} = p_{air} + p_{water} \tag{5}$$

When data from Baro-Diver are subtracted from corresponding data from Cera-Diver, it results in pressure exerted by the water column above the Cera-Diver at any point in time. The pressure exerted by the water column can be expressed as the height of water ($h$) above the pressure sensor [39]:

$$h(cm) = 9806.65\frac{p_{Cera-Diver} - p_{Baro-Diver}}{\rho \times g} \tag{6}$$

where

$p$ is the pressure in cm of water

$\rho$ is the density of the water (1,000 kg/m$^3$)

$g$ is the acceleration due to gravity (9.81 m/s$^2$).

## 3. Results and discussion

### 3.1. The water balance

A water balance technique was used to measure the amount of added water and its loss components, as stated in Equation (2). Since the measurements were made on a weekly basis between irrigation events after the permanent water was applied to the field, the change in root zone soil moisture storage ($\Delta S$) and increment of water incorporated in the plants ($\Delta V$) were assumed to be negligible. No precipitation ($RF$) occurred during the experimental period. The ground water table was more than 15 m below ground level at this site, therefore upward capillary flow into the root zone ($UP$) was zero. The procedure of lockup was adopted within a measurement cycle, therefore the influence of runoff ($RO$) or drainage out of the field became negligible. Seepage losses were minimised by lining the bank with plastic barrier and filling the adjacent bays with water. By considering the above and rearranging the parameters, the water balance Equation (2) becomes as:

$$IR = E + T + DP \tag{7}$$

where

$IR$ = amount of irrigation water

$E$ = direct evaporation from the water surface

$T$ = transpiration by plants

$DP$ = downward drainage out of the root zone

No attempt was made to measure the amount of irrigation water applied, but it was estimated from the measurement of other components (evaporation, transpiration and deep percolation) using the lysimeters. It is vital that better estimates of evaporation, transpiration and deep percolation are necessary because they play an important role to accurately determine the crop water requirements. Thus crop water requirements which are directly related to crop evapotranspiration (ET) vary depending on crop grown and its different growth stages.

### 3.2. Evaporation

Evaporation is the moisture lost in vapour form from the free water surface where rice is grown. Shading of the water surface by rice plants reduces evaporation. Therefore daily evaporation losses are less for rice planted at close spacing. Similarly, evaporation losses also decrease as a crop approaches maturity. Trials elsewhere have shown that over the entire rice-cropping season, evaporation accounted for about 40 per cent of total losses to the atmosphere, with transpiration providing the remainder [40]. In this study, average evaporation losses from Lysimeter A and from evaporation pan are shown in Figure 7. Readings from the Lysimeter A were obtained within an irrigation cycle (that is, between topping-up the bay). Readings from the evaporation pan were obtained between two consecutive re-filling processes. These dates for both measurements were not common in most circumstances. Therefore direct comparison of losses from Lysimeter A with those of evaporation pan using individual data was not possible in this case.

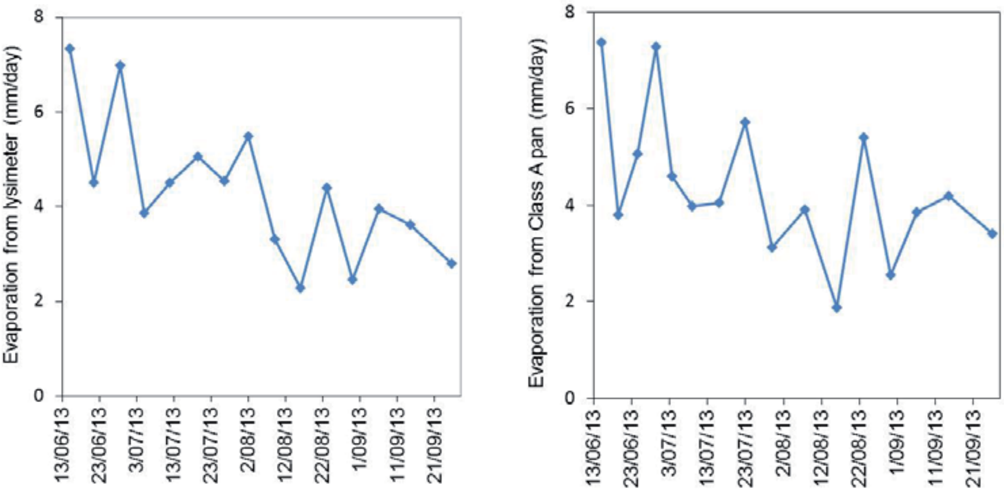

**Figure 7.** In-situ measurements of evaporation from Lysimeter A and Class A Evaporation Pan.

The data from this study shows that evaporation losses were high at 4-7 mm/day at the beginning when the rice plants were small. But it decreased to 3-4 mm/day when the crop developed full canopy. The shading effect of the crop canopy reduced the evaporation losses. The evaporation was not affected when the air temperature increased in August and September (Table 1). It should be noted that the shading effect was much greater than the air temperature effect on evaporation. Also note that the evaporation losses measured by the Lysimeter A and Class A Pan were close. Total evaporation losses obtained from Lysimeter A over a period of 90.5 days were 375.7 mm. Readings from Class A Pan over a period of 91.2 days resulted in 377.9 mm. Therefore, it can be concluded that for the purpose of reporting evaporation losses from a flooded rice bay, data from either Lysimeter A or Class A Pan could be used.

### 3.3. Transpiration

Transpiration is a process by which plants release water vapour to the atmosphere. It occurs through stomatal openings in the plant foliage in response to the atmospheric demand. The amount of water lost as transpiration usually reaches a maximum value during the day and the minimum value during the night. Crop transpiration losses were measured in this experiment as the difference in water lost between Lysimeter C and Lysimeter B and the results are shown in Figure 8.

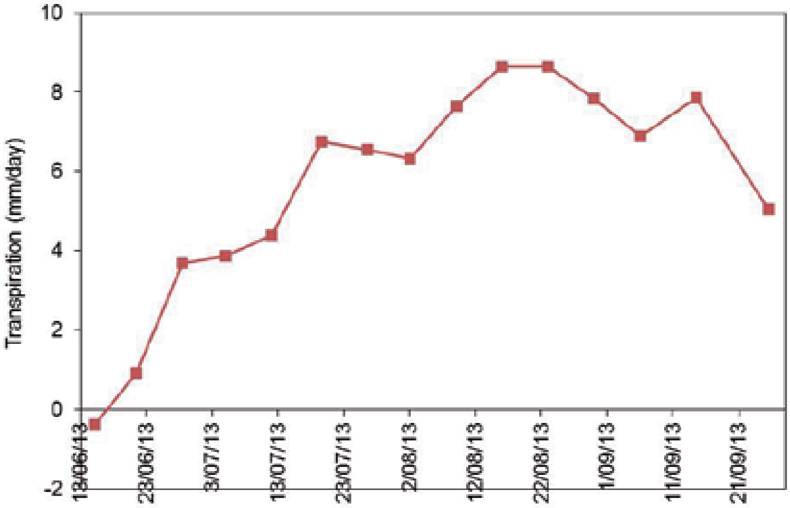

**Figure 8.** Transpiration losses as measured by the lysimeters.

Transpiration losses at the beginning were lower due to small size of the rice plants at that time. The crop was first irrigated on 12 May 2013. Permanent water was applied on 12 June 2013. Therefore the plants were 31 days old when the experiments started. Slightly negative value for transpiration during the first irrigation cycle was unexpected. The negative value indicated that the average losses from Lysimeter B were slightly higher than that of Lysimeter C. The only difference between these two lysimeters was that Lysimeter C contained rice plants at an early stage whereas no plants were left in Lysimeter B. Because the losses recorded at this stage were very small, this deviation in results (negative value) was ignored.

Transpiration losses increased rapidly as the plants reached full canopy and then started to decline when the plants approached full maturity. The increase in transpiration was mainly due to more leaf surface area contributing to more stomata openings for water loss. At full canopy, transpiration losses (8.6 mm/day) were almost double of evaporation losses (4.4 mm/day). Over the period of 90.5 days, the total transpiration losses were 523 mm. Over the period of measurement, evaporation accounted for about 41.8 per cent of total losses to the atmosphere, with transpiration providing the remainder of 58.2 per cent, similar to the results reported in [40]. The transpiration losses reported in this study are for rice variety IR 72 at plant population of 200-300 plants/$m^2$. Note that the transpiration losses might be different for another rice variety and for different plant densities.

### 3.4. Deep percolation

Percolation in a flooded rice field is considered as the downward movement of free water through saturated soil due to gravity and hydrostatic pressure exerted by the ponded water.

Percolation losses are a function of the local soil conditions and the depth of water over the soil surface. When the texture of the soil is heavy (about 70% clay), percolation losses are low (<1 mm/day). Field studies in the Philippines in the dry season have shown mean percolation rates of 1.3 mm/day on alluvial and elastic soils with shallow water tables (< 2m), and 2.6 mm/day when the water table was deeper (> 2m) [41]. The seasonal-average percolation rate as measured in percolation rings was 1.7 mm/day in the dry season and 0.7 mm/day in the wet season at Los Baños in the Philippines [42]. The deep percolation losses as measured in this experiment using Lysimeter B and Lysimeter A are shown in Figure 9.

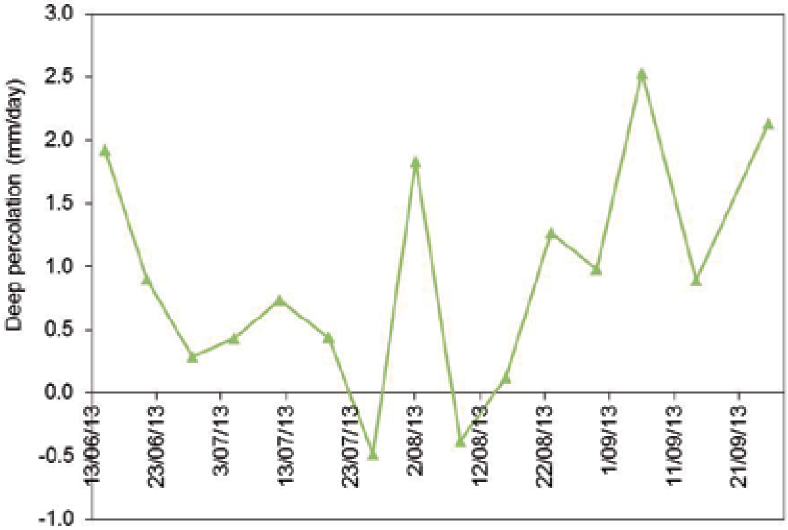

**Figure 9.** Deep percolation losses as measured by the lysimeters.

Over the period of measurement, the deep percolation losses varied between approximately 0 and 2 mm/day. This variability in measurement might be due to the nature of measurements carried out in Lysimeters A and B. A total of 87.9 mm deep percolation losses occurred over a period of 90.5 days. This indicates that the average deep percolation loss over the period was 0.97 mm/day. These findings are supported by studies conducted by [43] who found that surface water infiltrated no deeper than 1.07 m into Cununurra clay after surface ponding for 54 hours. Similar results were reported by [44] who found no evidence of upward or downward movement of soil water below a depth of around 1.65 m in Cununurra clay. Much more recently, [45] concluded there was negligible deep drainage below furrow-irrigated sugar cane grown on Cununurra clay. However, higher infiltration rates reported by others [44,46,47] may be attributed to the presence of well-developed slickensides and shrinkage cracks (Table 2) that penetrated the transition zone between Cununurra clay and the underlying lighter textured soil at some locations [48]. Previous flooded rice systems in Cununurra clay in areas where a shallow clay layer overlying a more porous sandy profile were attributed to have contributed to excess groundwater recharge rates [49].

The average deep percolation of 0.97 mm/day as determined in this study was less than previously reported in Cununurra clay, perhaps reflecting improved crop and water management practices used with modern rice varieties. With ponding, the clay swells and the cracks are resealed. Thus irrigation water is unable to infiltrate further than a few metres into Cununurra clay soil under extended period of ponding. However, under furrow-irrigation, soil tends to crack between irrigation events and this phenomenon may have contributed to high infiltration rates. Leakage rates under furrow irrigation were estimated to be 160 to 250 mm/irrigation season for cotton in Queensland [50], 11 to 101 mm/season for maize and between 190 and 340 mm/crop-cycle for sugarcane, both in the Ord River Irrigation Area [51]. Thus the leakage under ponded rice culture compares well with irrigated cotton or sugarcane in the Ord River Irrigation Area.

Climatic conditions can impact on processes such as evaporation and transpiration, but have no effect on deep percolation. If this low level of deep percolation can be replicated at the paddock and farm scale, it is predicted that recharge of groundwater under extensive rice cultivation using the traditional flooded system in Cununurra clay soil should be within manageable limits. If these experimental results can be translated to paddock and whole farm scales, the deep percolation rates under flooded rice system would not be a problem for the growers or environmental managers, regarding rising groundwater levels, waterlogging and salinity.

### 3.5. Total water use

In the early stages of the rice crop, immediately after ponding, most water lost from rice field was evaporation. Once the crop developed a full canopy cover, transpiration accounted for most of the water used. The combined losses of water from evaporation and transpiration (referred as evapotranspiration) averaged 9.93 mm/day over the period of measurement of 90.5 days. In most of the tropics, the average evapotranspiration during the dry season was found to be 6-7 mm/day [23]. The higher value for evapotranspiration reported in this study might be due to not including the data during the first 31 days of the crop. Data during the first 31 days were not collected in this study. The maximum value of evapotranspiration (13.04 mm/day) was reached at heading time and it was found to be 2.96 times of the evaporation at this site during 2013.

Evaporation pans provide measurements that integrate the effect of climatic factors such as solar radiation, wind, temperature and humidity on evaporation from open water surfaces. Thus, in several countries, data from Class A Evaporation Pan (installed in the rice field) have been correlated with measured actual evapotranspiration. In this experiment, over a period of 90.5 days, the average evapotranspiration was found to be nearly 2.4 times higher than the average evaporation from Class A pan. Trials elsewhere have found that over the whole rice crop growth period, the evapotranspiration from rice field was 1.2 times more than open pan evaporation [52]. In the present study, evaporation losses during the initial period of 31 days were not measured. Even assuming a highest value of 7 mm/day of evaporation during this initial period and negligible transpiration, the adjusted average evapotranspiration could still be 1.9 times more than the average evaporation.

The sum of evaporation, transpiration and deep percolation losses as measured by the lysimeters is considered as total water losses. This is compared with the total field losses as measured outside the lysimeters (i.e. field water level) in Table 3. The total water loss reached a maximum value of 14.3 mm/day for the lysimeter measurements. However the field losses reached a maximum of 10.1 mm/day. This difference in measurement was mainly due to the fact that the lysimeter had 100% cropped area and the surrounding field had only 33.1% cropped area. The trial was established to compare the yield performance of five different rice varieties replicated three times. Hence one metre of bare land was allowed between the plantings in order to separate the treatments. Buffer area around the trial area also followed the same planting configuration. In addition, the head-end and tail-end of the bay had some bare land without any crop planted. Note that the difference in cropped area between lysimeters and surrounding field had a direct effect only on the amount of transpiration losses. Based on the cropped area, this translates into the total transpiration losses from the surrounding field were only a third of that measured in the lysimeters. The initial two readings obtained from water level fluctuation of the surrounding field (that is 9.40 and 10.08 mm/day in Table 3) were possibly due to seepage losses to the neighbouring bay which had its permanent water only on 26 June 2013.

| Date | Total water loss in lysimeters (mm/day) | Total water loss in field (mm/day) |
|---|---|---|
| 15/06/2013 | 8.88 | 9.40 |
| 21/06/2013 | 6.33 | 10.08 |
| 28/06/2013 | 10.96 | 6.49 |
| 05/07/2013 | 8.16 | 3.90 |
| 12/07/2013 | 9.64 | 5.75 |
| 19/07/2013 | 12.25 | 3.28 |
| 26/07/2013 | 10.60 | 4.98 |
| 02/08/2013 | 13.63 | 6.34 |
| 09/08/2013 | 10.59 | 5.18 |
| 16/08/2013 | 11.05 | 4.60 |
| 23/08/2013 | 14.31 | 9.95 |
| 30/08/2013 | 11.26 | 5.46 |
| 06/09/2013 | 13.36 | 9.77 |
| 14/09/2013 | 12.35 | 9.60 |
| 25/09/2013 | 9.97 | 9.05 |

**Table 3.** Total water losses from flooded rice system within lysimeters and outside in the field

The difference in water level within lysimeters and outside as shown in Figure 4 may have created a hydraulic difference (applicable to open-end type Lysimeters B and C only). At the end of irrigation (topping-up), water levels in and out of lysimeters remained at the same level. However, towards the end of the irrigation cycle, water levels inside the Lysimeters A and B remained higher than outside water level. But water level inside Lysimeter C remained lower than outside. Lysimeter A had closed bottom and therefore the difference in water level had no influence on measured values. In Lysimeter B, some water might have moved out due to the hydraulic difference created by different water levels in and out of the lysimeter. The implication of this effect was over estimation of deep percolation losses in this experiment and the actual value of deep percolation might be less than the reported value of 0.97 mm/day. On the other hand, water level inside Lysimeter C was lower than outside towards the end of the irrigation cycle. Therefore some water might have moved into the lysimeter due to the hydraulic difference and contributed to under estimation of transpiration losses in these experiments. In other words, the actual transpiration losses might be higher than the measured values.

The error in the measurement of transpiration and deep percolation due to the difference in water levels was calculated according to the procedure outlined by [53]. For Cununurra Clay soil, the value of hydraulic conductivity as $10^{-7}$ m/sec [34,47] and infiltration rate as 0.02 cm/min [43,47] were assumed in the calculation of error. For the lysimeter conditions that prevailed in this experiment, the error in the measurements of deep percolation and transpiration was found to be about ±2 per cent which was assumed to be negligible. Conditions such as larger diameter (50 cm) of the lysimeters, their deeper penetration (35 cm) into the soil, and smaller difference (<4 cm) in water levels have contributed to the negligible error in measurements in this experiment compared with the results reported by [53].

### 3.6. Water productivity

The water productivity values depend on the type of cereal crop under consideration and whether the crop evapotranspiration or the irrigation water is used in the calculation. In this study, water productivity was calculated with respect to the amount of water evaporated and transpired ($WP_{ET}$) and with respect to total water input ($WP_{IR}$) [54-56].

$$WP_{ET} = \frac{Y}{\sum(E+T)} \left(\text{g grain kg}^{-1}\text{water}\right) \tag{8}$$

$$WP_{IR} = \frac{Y}{\sum(IR+RF)} \left(\text{g grain kg}^{-1}\text{water}\right) \tag{9}$$

where

$Y$ is the grain yield expressed in g m$^{-2}$

$E$ is the evaporation expressed in kg water m$^{-2}$

$T$ is the transpiration expressed in kg water m$^{-2}$

$IR$ is the irrigation expressed in kg water m$^{-2}$

$RF$ is the rainfall expressed in kg water m$^{-2}$

Note that no rainfall (*RF*) occurred during the trial period and the amount of irrigation (*IR*) is represented by Equation (7) that includes deep percolation losses as well. Water productivity expressed in different units can be compared using Equation (10) as:

$$\frac{g_{grain}}{kg_{water}} = \frac{kg_{grain}}{m^3_{water}} = \frac{t_{grain}}{ML_{water}} \tag{10}$$

The total water losses as measured by the lysimeters over the period of 90.5 days were 986.6 mm where 38% accounted for evaporation, 53% for transpiration and 9% for deep percolation. Ponded water was maintained for the rice crop in this trial for 112 days. Hence the above reported results were extrapolated to cover the entire duration of ponding of 112 days. This resulted in 1220.5 mm. According to conversion presented in Equation (3), 100 mm of water depth equals to 1 ML/ha, and therefore the total water loss would be approximately 12.21 ML/ha. No drainage occurred before harvest as the last application of irrigation water was allowed to be used by the crop during grain ripening stage. It can be assumed that the two flushings carried out before the permanent water must have used a further 1 ML/ha in total. Therefore the 2013 rice crop total water usage amounts to 13.21 ML/ha. This compares well with the rice crop water use of 18.4 ML/ha for conventional ponded rice grown on a flat layout at Coleambally in New South Wales in Australia [57]. Compared with other crops such as sugar cane in the Ord River Irrigation Area which requires approximately 18 ML/ha of water, i.e. 12 ML/ha during dry seasons and 6 ML/ha during wet seasons [58], rice appears to require less water.

Mean grain yields of five varieties tested at this site during the trial (Figure 10) varied from 5.76 t/ha (for the variety, Doongara) to 12.66 t/ha (for the variety, Viet 1). The average yield of all five varieties was found to be 9.74 t/ha. These five varieties and the buffer shared equal proportions in area for the bay used in this study. No attempt was made to determine the grain yield of buffer (IR 72) where lysimeters were located. However, visual assessment of the buffer area indicated a yield similar to 9-10 t/ha was possible for this variety, IR 72. Hence, the overall average yield of 9.74 t/ha was used to calculate the water productivity values for this experiment.

A value from 0.42 to 0.60 kg/m$^3$ has been cited for rice water productivity in Australia [59]. In contrast, a trial in south-eastern Australia found that the water use efficiency of conventional ponded rice was 0.68 t/ML [57]. In the Philippines, under flooded conditions, water productivity with respect to total water input ($WP_{IR}$) ranged from 0.22 to 0.34 g grain kg$^{-1}$ water and $WP_{ET}$ ranged from 1.50 to 2.12 g grain kg$^{-1}$ water [42]. A trial in India indicated that water productivity in continuous flooded rice was typically 0.2–0.4 g grain per kg water [55]. The average water productivity of rice for conventional method (transplanted puddled rice) in Punjab in Pakistan varied from 0.27 kg/m$^3$ [60] to 0.34 kg/m$^3$ [61]. In the present study, water productivity as calculated with respect to the amount of water evaporated and transpired ($WP_{ET}$) was 0.73 t/ML and with respect to total water input ($WP_{IR}$) was 0.74 t/ML. The value for $WP_{ET}$ reported in this study was lower than that reported by [42]. However, the value for $WP_{IR}$ in this study was significantly higher than those reported in references [42,55,57,59-61].

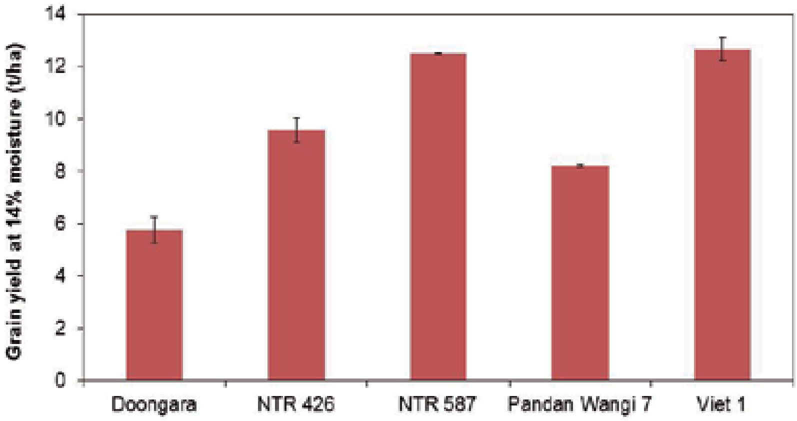

**Figure 10.** Mean yield of varieties tested at the trial site (error bars indicate standard error).

Hence the conventional ponded rice culture similar to that adopted in this trial was highly efficient for rice production on Cununurra clay in the tropical environment, specifically for the variety IR 72 and for the environmental conditions experienced during the dry season of 2013.

## 4. Conclusion

Water will be a major constraint for agriculture in coming decades, particularly in Asia and Africa. In densely populated arid areas, such as Central and West Asia, and North Africa, water is scarce and availability of water is projected to be less than 1 ML per capita per year. This scarcity of water relates to irrigation water for food production [19]. To increase crop yield per unit of scarce water requires both better cultivars and better agronomy. Under field conditions, the upper limit of water productivity of cereal crops is estimated to be around 20 $kg.ha^{-1}.mm^{-1}$ (grain yield per water used, equivalent to 2 t/ML) [62]. If the water productivity value is less than this, it can be due to major crop stresses other than water, such as weeds, pests, diseases, poor nutrition, or other soil limitations. Under these circumstances, the greatest improvement can be achieved from alleviating these issues first.

In response to water scarcity and environmental concerns, the amount of water input per unit irrigated area will have to be reduced. Water productivity of rice is projected to increase in many countries through gains in crop yield and/or reductions in irrigation water. Selecting locally adapted modern varieties have potential to lift the yield level in many rice growing areas. For example, a rice variety from Vietnam tested in the tropical climate of the Ord River Irrigation Area achieved a highest yield of 14.3 t/ha in this environment [14]. Saving water is possible by reducing seepage, percolation and runoff losses from fields. This requires that the components of the water balance need to be quantified (similar to the study reported here).

A review of literature which reported on rice water productivity values for the tropical regions shows an average of 0.295 t/ML compared to 0.74 t/ML as found in this study. This difference in water productivity translates into about 2 ML of water saving for every tonne of rice produced in most tropical regions. If the world rice production is about 700 million tonnes and over 90 per cent of the world's rice is produced in the Asian Region, the improved water productivity could save huge amount of irrigation water in the Asian region. With increasing water scarcity for irrigation, productivity of current rice production systems has to be improved substantially to feed an ever-increasing world population. It is vital to use locally adapted high yielding varieties together with appropriate water management techniques to achieve higher water productivity. Although seepage and runoff losses can be minimised, deep percolation losses are difficult to control. Puddling is a technique used to minimise deep percolation losses. However, direct dry seeding techniques are widely used to save labour costs. In this case, more attention must be paid towards choosing appropriate soil types for flooded rice production systems.

Many technologies appear to save substantial amounts of water through reducing irrigation water requirements. For example, a shallow intermittent irrigation saved 32% of irrigation water compared to traditional deep water irrigation without any effect on yield in Korea [63]. Another study in Panjab in Pakistan found that the direct seeding of rice saved 25% water compared to conventional method of transplanted rice and water productivity increased from 0.27 kg/m$^3$ for conventional method to 0.32 kg/m$^3$ for direct seeding [60]. Similar improvement of water productivity was reported by [61] for direct seeding method for rice (0.41 kg/m$^3$) compared with conventional method (0.34 kg/m$^3$). Note that the present trial reported here used the direct seeding technique to save irrigation water requirement.

It is questionable whether moving away from ponded rice culture to more aerobic rice culture results in improved water productivity. A trial conducted at Coleambally in New South Wales in Australia found that the water use efficiency of the raised bed system (0.55 t/ML) was lower than the conventional ponded rice (0.68 t/ML) [57]. Yield was reduced from 12.7 t/ha in the conventional method to 9.4 t/ha in the furrow irrigated bed treatment in this trial. In terms of irrigation water use, furrow treatment used 17.2 ML/ha while the ponded treatment used 18.4 ML/ha. The increase in length of growing season for the bed treatment also increased the period of irrigation, thus reducing the potential for water savings.

Rice grows well and produces best under flooded conditions but large amount of water is needed for this system. However, reducing water use through an aerobic system of rice production that eliminates maintenance of ponded water is necessary to mitigate a looming water crisis. There is no doubt that increased demand for food will be met by the products of irrigated agriculture. To evaluate the potential of aerobic rice system in the tropics, a field trial on aerobic rice was conducted at the International Rice Research Institute (IRRI) [64]. This study found that aerobic rice saved 73% of irrigation water for land preparation and 56% during the crop growth stage. However, aerobic rice yields were lower by an average of 28% in the dry season and 20% lower in wet season. Yunlu 29 (a tropical variety from Yunnan Province in China which is adapted to aerobic conditions) has shown potential for high yield (10-12 t/ha) in the Ord River Irrigation Area under optimum moisture conditions [15,65]. Further experiments and breeding of varieties better suited to aerobic conditions are needed.

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The sustainability of irrigation and drainage in the face of many variants and constraints like availability of water as a resource, ecological balance, socio-cultural impacts, and climate change effects lies in the strategies adopted and systems emplaced. It has always remained a challenge for the users of irrigation waters to maintain sustainability in quality and quantity. This book aims ?to explore frontiers of knowledge in coining sustainable strategies and systems direly needed in managing the quality and quantity of water required for crop irrigation, surface and root zone drainage and flood management using available tools of research and development?. Eminent authors and their colleagues possessing varied professional backgrounds and expertise have dealt with these issues concerning the strategies and systems of irrigation and drainage. This book will prove to be beneficial for crop growers, agricultural engineers, water resource managers, academicians and graduate students alike.

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