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Achievements and Challenges of Integrated River Basin Management

Edited by Dejan Komatina

ACHIEVEMENTS AND CHALLENGES OF INTEGRATED RIVER BASIN MANAGEMENT

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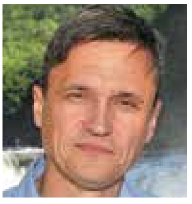
Meet the editor



Dejan Komatina holds his PhD degree in Civil Engineering with a focus on environmental river engineering. He has over 28 years of national and international experience in the water- and environment-related fields in a wide range of roles—as a university teacher, a scientist, a professional engineer, and a manager of international organizations dealing with water and environmental issues—International Sava River Basin Commission (ISRBC) and the Regional Environmental Center for Central and Eastern Europe. As the first-ever executive secretary of ISRBC for over 11 years, he coordinated the member countries' cooperation in the areas of water management, environment protection, climate change, sustainable waterway transport, and river tourism for the establishment of sustainable management and development of water resources in the major basin of Southeast Europe.

Contents

Preface

Integrated river basin management focuses on the development and management of land and water resources in a coordinated manner, with the primary aim to ensure society development that is well-balanced from the environmental, economic, and social points of view. Integrated river basin management includes all aspects of water resources management, i.e., the sustainability issues, such as protection of aquatic ecosystems, protection against water-related disasters (floods, droughts, ice, accidents involving water pollution), as well as the development activities associated with the use of water resources (inland navigation, hydropower generation, agriculture, fishery, tourism, and recreation). By addressing all the elements of land and water resources (soil, sediment, surface water, groundwater) and related ecosystems, integrated river basin management covers a wide range of disciplines (e.g., hydrology, ecology, environmental management, economy), cross-cutting issues (climate change impact assessment and adaptation, data and information exchange and management, public participation and stakeholder involvement) and approaches (river basin management plan preparation, water-food-energy-ecosystems nexus assessment, science-policy integration, transboundary cooperation).

This book provides the reader with a comprehensive overview of achievements and challenges associated with the implementation of the integrated river basin management approach through a selection of papers with global geographical relevance, as well as case studies from all over the world. The book is divided into four sections. Section 1 is focused on water quality and quantity as key inputs for river basin management, and includes two case studies on the assessment of surface water quality (Chapter 1) and groundwater (Chapter 2), and two papers dealing with hydrology of specific geographical areas (Chapter 3) and data scarce regions (Chapter 4). Section 2 elaborates various aspects of flood and drought management, such as hydrological and hydraulic modelling as a basis to evaluate the impact of flood mitigation measures on flood safety (Chapter 5), the role of local community in ensuring a better response to flood disasters (Chapter 6), and the performance of a managed aquifer recharge for sustainable management of groundwater resources in a drought prone area (Chapter 7). Transboundary issues of river basin management are elaborated on in the two chapters of Section 3, describing the transboundary water cooperation process coordinated by a river basin organization (Chapter 8), and challenges associated with the water quantity and quality monitoring in a transboundary region (Chapter 9). Section 4 deals with a range of water governance issues, including the integration of information-communication technologies in water resource management as a basis for sustainable development at global scale (Chapter 10), the contribution of local resource users and community-based organizations to better river basin management through their involvement in decision-making processes (Chapter 11), and a comparative analysis of the policy and governance contexts of several regions affected by different hydrological impacts of climate change (Chapter 12).

It is hoped that the diversity of topics covered in the book will contribute to a better understanding of the integrated river basin management approach, and increase awareness of its complexity, associated opportunities, as well as the need for implementation of this approach as a basis for sustainable development of river basins throughout the world.

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Section 1

Water Quality and Quantity as Management Inputs

Chapter 1

Seasonal Variation of the Physico-chemical Composition of Ottawa River Waters in the St. Lawrence River

Jean-Jacques Frenette and Ali A. Assani

Additional information is available at the end of the chapter

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Abstract

The goal of this study is to compare the seasonal variability of 12 physicochemical characteristics of waters in the Ottawa and St. Lawrence Rivers (SLR). Water samples were collected on board the research vessel *Lampsillis* in the spring (May), summer (August), and fall (October) of 2006 at four stations located downstream from the confluence of the two rivers. Temperature and total nitrogen values varied significantly for the three seasons. In contrast, seasonal values of light extinction coefficient and turbidity do not show any significant variation. The values of the other characteristics varied significantly only for one season. Comparison of these data with those measured in 1994–1996 reveals a net warming of the waters and a significant increase in nitrite-nitrate concentrations due to the increasing use of nitrogen-bearing fertilizers by farmers in Quebec. Concentrations of these two substances are higher than the limits set by the government of Quebec for water quality in rivers.

Keywords: physicochemical characteristics, seasons, ANOVA, Kruskal-Wallis test, Ottawa River, St. Lawrence River

1. Introduction

The St. Lawrence River (SLR) forms a complex system composed of a mosaic of heterogeneous zones such as fluvial lakes, connecting reaches and wetlands, which interact with inflowing tributaries to produce strong longitudinal and lateral connectivity between aquatic and terrestrial environments (reviewed in [1]). The tributaries flow through a watershed covering 1,600,000 km^2, where land use is dominated by a high degree of urbanization near Montreal and areas of agriculture, pasture, forests, and wetland in the mid- and lower reaches of the stream system [2, 3]. Water intrusions from tributaries contribute to the formation of several parallel water masses with distinct physical and chemical properties. Among these, the Ottawa River plays a significant role in structuring the biogeochemical properties of the brown water river considering its strong discharge rate and largely human impacted watershed [4].

Many studies have analyzed the physicochemical and biological characteristics of these waters (e.g., [5–24]) and of related sediments [25–28], while other studies focused on optical characterization of these waters (e.g., [27–32]). Most of these studies analyzed the spatial variability of these characteristics in the St. Lawrence River, but very few looked at their seasonal and interannual variability. One notable exception [12] compared the interannual variability of these characteristics measured upstream and downstream from the confluence of the Ottawa and St. Lawrence Rivers from May through September, from 1994 to 1996. However, the changes in physicochemical characteristics of Ottawa River waters flowing through the St. Lawrence River were not specifically studied at the seasonal or decadal level. The main goal of this study is to analyze the seasonal variability in physical and chemical properties of the Ottawa River water mass flowing in the St. Lawrence River along 80 km further downstream from the confluence. Water characteristics were measured at four stations in the spring (May), summer (August), and fall (October) of 2006, something that has never been analyzed. The secondary goal of the study is to compare these characteristics with those measured 10 years earlier by [12].

2. Description of the Ottawa River watershed

The Ottawa River, which is the main tributary of the St. Lawrence River, takes its source in Lac Capimitchigama (**Figures 1** and **2**). Stretching over approximately 1130 km, the Ottawa drains a 146,334 km^2 watershed. From a geological standpoint, the river flows mainly through the Canadian Shield, which comprises Archean and/or Proterozoic igneous rocks, as well as Proterozoic metasedimentary and intrusive rocks. Upstream of its confluence with the St. Lawrence River, the Ottawa River flows through the relatively flat St. Lawrence Lowlands, comprising carbonate and siliciclastic sedimentary rocks. Climate in the watershed is cool continental temperate, characterized by very cold and snowy winters and warm and relatively dry summers. Temperatures and precipitations decrease from south to north in the watershed. From a hydrographic standpoint, 19 main tributaries flow into the Ottawa River, of which the primary ones are the Gatineau, Lièvre, Kipawa, Rouge, Madawaska, Montreal, Blanche, and Petawawa. The Ottawa River watershed also includes over 90,000 small and large lakes.

The Ottawa River and most of its tributaries are heavily regulated, the watershed comprising more than 1000 small and large dams, in addition to 30 large reservoirs built to control flood flows. Reservoirs built in the upper reaches of the watershed have inverted the annual cycle of flows such that maximum flows occur in winter and minimum flows in springtime during snowmelt, contrary to the annual flow regime in natural rivers. This inversion, however, fades gradually in the lower reaches of the watershed due to input from natural tributaries (**Figure 3**). Annual mean discharge in the Ottawa River at its confluence with the St. Lawrence River is roughly 1980 m^3/s [12], and the watershed is almost completely covered by forests

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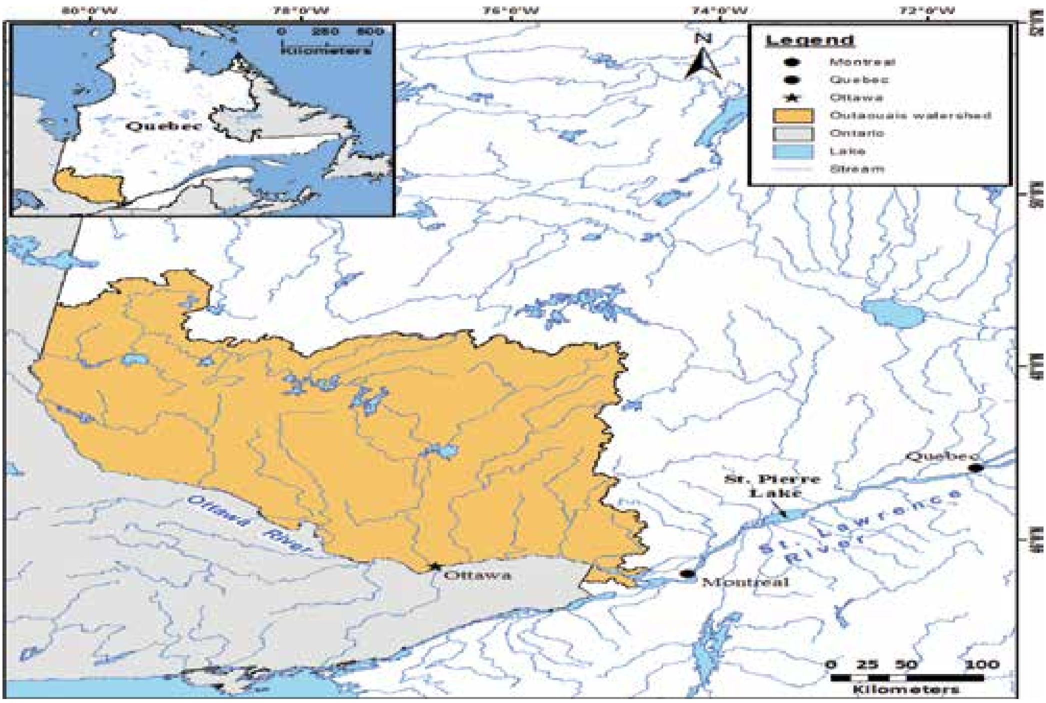

Figure 1. Location of the Ottawa River watershed and the St. Lawrence River.

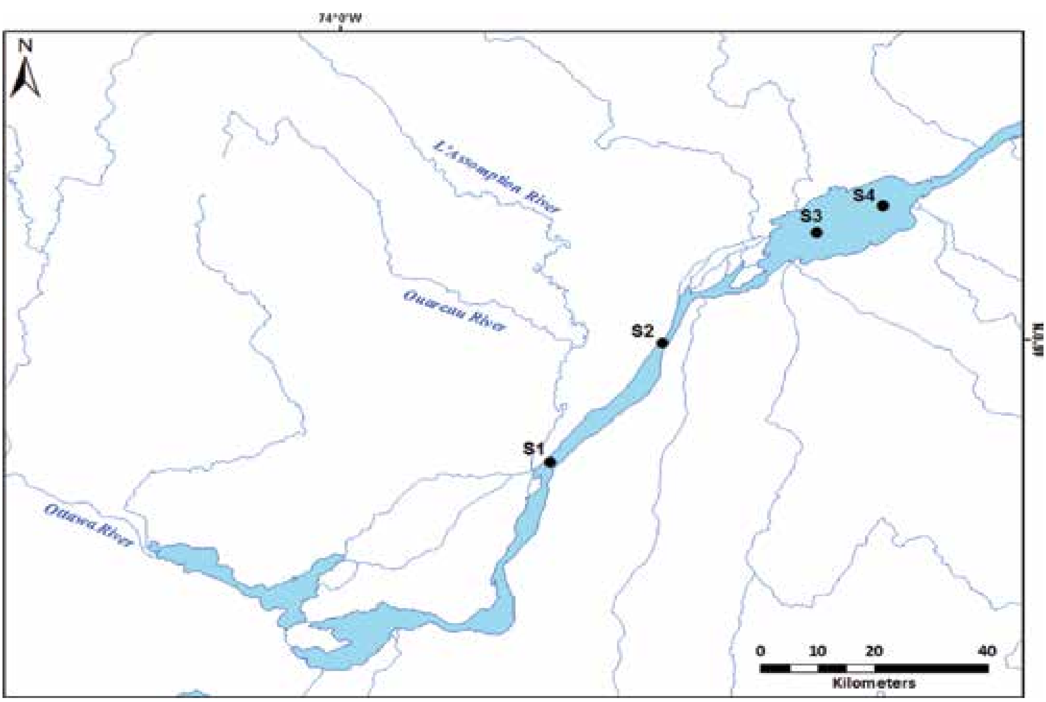

Figure 2. Location of sampling stations along the St. Lawrence River.

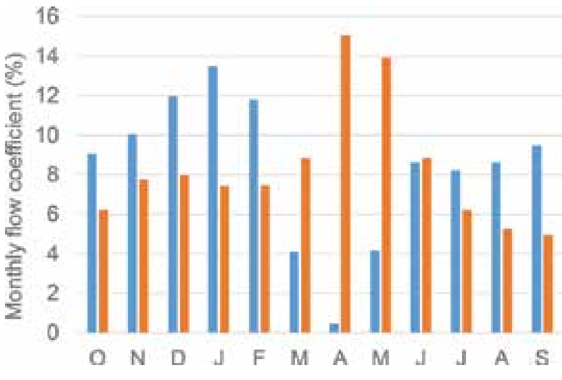

Figure 3. Monthly flow coefficients downstream from the Dozois reservoir (blue bars, 8210 km^2) and the carillon dam (red bars, 143,000 km^2) built on the main branch of the Ottawa River.

(deciduous, mixed, and boreal). Farming is only practiced in the lower part of the watershed and accounts for only 3% of its total surface area. The main urban areas in the watershed are the Ottawa-Gatineau and Laval areas.

3. Analysis of the chemical and physical variables of waters

Three 8-day sampling cruises were conducted in the St. Lawrence River (SLR) during spring (23–30 May), summer (9–15 August), and fall (11–17 October) 2006 aboard the RV "Lampsilis" from the Université du Québec à Trois-Rivières. We studied the SLR along a 450 km distance from its source at the outlet of the Great Lakes, until the interface with marine waters at the estuarine transition zone (ETZ), 50 km downstream from the marine intrusion (**Figure 1**). Water samples were collected at the surface (0.5–1.3 m) for all stations using a Go-Flow bottle (8 L) and immediately processed in the wet laboratory after collection.

Sampling was carried out at four stations in the water mass entering from the Ottawa River along 80 km downstream transect (**Figure 2**). At each site, water was subsampled directly in acid-washed bottles for total phosphorus (TP) and total nitrogen (TN) measurements. For soluble reactive phosphorous (PO_4) and for nitrites (NO_2) and nitrates (NO_3), samples were filtrated on 45 mm diameter, 0.7 μm poresize GFF filters (Millipore). PO_4 was analysed using the acid molybdate technique. NO_3 was first reduced into NO_2 by cadmium, and the nitrite concentrations were determined by the sulfanilamide method.). TP and TN concentrations (check) were obtained using the spectrophotometric determination of phosphates and nitrates after digestion by potassium persulfate. All phosphorus and nitrogen analyses were performed according to the American Public Health Association protocols [33]. We used a multiprobe depth profiler (YSI, model 6600EDS-M, Yellowspring Inc.) to measure the conductivity, temperature, and turbidity of the water column. Values for the surface of the water column were averaged between 0.5 and 1.5 m. Physicochemical variables or characteristics of St. Lawrence River waters analyzed as part of this study are presented in **Table 1**.

Variables	May (M1)	August (M2)	October (M3)	Results of comparison of mean values
Temperature (°C)	12.9 (0.78)	23.3 (0.21)	13.9 (0.17)	M1 ≠ M2 ≠ M3
Total nitrogen (TN, mg/L)	4.52 (2.47)*	3.05 (0.70)*	0.70 (0.33)*	M1 ≠ M2 ≠ M3
Nitrite (NO_2, mg/L)	9.19 (2.93)*	0.008 (0.003)	1.79 (0.53)*	M1 ≠ (M2 = M3)
Total phosphorous (TP, μg/L)	61.60 (30.89)*	23.47 (12.21)	8.65 (3.17)	M1 ≠ (M2 = M3)
$aCDOM_{340nm}$ (m^{-1})	15.79 (5.75)	7.92 (1.65)	3.11 (1.35)	M1 ≠ (M2 = M3)
Nitrate (NO_3, mg/L)	0.53 (0.43)*	0.73 (0.21)*	0.55 (0.40)*	M2 ≠ (M1 = M3)
Phosphate (PO_4, μg/L)	5.24 (1.03)	10.29 (1.89)	2.20 (1.99)	M2 ≠ (M1 = M2)
Transmittance (trans, %)	24.43 (19.19)	63.28 (8.88)	79.04 (1.11)	M2 ≠ (M1 = M3)
Conductivity (cond, μS/cm)	0.062 (0.019)	0.072 (0.009)	269.0 (4.65)	M3 ≠ (M1 = M2)
Light extinction coefficient (($K_{d(PAR)}$) m^{-1})	2.46 (0.38)	1.81 (0.23)	0.97 (0.103)	(M1 = M2 = M3)
Turbidity (TURB, NTU)	9.41 (4.13)*	9.39 (6.80)*	4.47 (1.37)*	(M1 = M2 = M3)

(M1≠ M2≠ M3): mean values are significantly different at the 5% level (all statistical tests used).
(M1= M2): mean values are not significantly different at the 5% level (all statistical tests used). (0.78) = standard deviation.
*The mean concentration exceeds the provincial standard limit value.

Table 1. Comparison of seasonal mean values of physicochemical variables measured at four stations in St. Lawrence River water influences by the Ottawa River in 2006.

As far as *a*CDOM measurements, water samples for the absorption coefficient of chromophoric dissolved organic matter (*a*CDOM) and DOC were filtered through Milli-Q-rinsed 0.22 μm Isopore membrane (millipore) and stored them in the dark at 4°C until analysis. We measured CDOM absorption spectra in a 10 mm quartz cell at 1 nm intervals between 190 and 900 nm using a spectrophotometer (Shimadzu UV-2401PC) referenced against Milli-Q water. We used absorbance at 690 nm (where the temperature dependency is near zero) to correct the UV absorption values. We converted absorbance values at 340 nm to absorption coefficients ($aCDOM_{340nm}$) using the following equation [8]:

$$aCDOM_{340nm} = \frac{2.303 A_{340nm}}{L} \tag{1}$$

where L is the cuvette path length (0.01 m).

As far as spectral radiation and beam attenuation measurements are concerned, photosynthetically available radiation (PAR) (400–700 nm) in the water column was measured at each station as in [1]. Briefly, downward irradiance was measured at every 0.02 m with a spectroradiometer (Model Hyperpro, Satlantic Instruments), which was slowly lowered through the water column to measure depth profiles of the cosine-corrected downwelling underwater irradiance (E_d) at every 3 nm between 351 and 750 nm (100 wavebands). Light data were corrected automatically for "dark irradiance" values obtained from the shutter darks.

Diffuse attenuation coefficients ($K_{d(PAR)}$) were calculated by linear regression of the natural logarithm of E_d versus depth. E_d values correspond to PAR. The Hyperpro was equipped with a C-star transmissometer (Wet Labs Inc., 25 cm path length, λ = 660 nm) to measure depth profiles of the scattering of underwater particles (trans) such as sediments.

Statistical analysis consisted of comparing seasonal mean values of physicochemical variables measured at the four stations using the analysis of variance approach when the data were normal and the Kruskal-Wallis test when the data were not. The same statistical tests were used to compare mean values of certain characteristics at the decadal scale and those of seasonal water levels. Water level data for the St. Lawrence River, taken from the Environment Canada website (https://eau.ec.gc.ca/download/index_f.html?results_type=historical, viewed on September 20, 2017) and measured at the Lanoraie station (ID: 02OB011; 45°57′33″ N, 73°15′52″W) since 1990, are strongly influenced by water masses entering from the Ottawa River.

4. Results and discussion

4.1. Seasonal variability

In order to characterize the 2006 hydrological year, water levels measured in the St. Lawrence River in 2006 were compared with mean water levels derived for a 20-year period (1990–2010) at the Lanoraie station (**Figure 4**). For the 3 months during which sampling was done, mean water levels were higher than the 20-year calculated mean for the months of May and October 2006 but equal for the month of August.

A comparison of seasonal mean values of physicochemical variables reveals that mean values of temperature and total nitrogen (TN) are significantly different for the three seasons

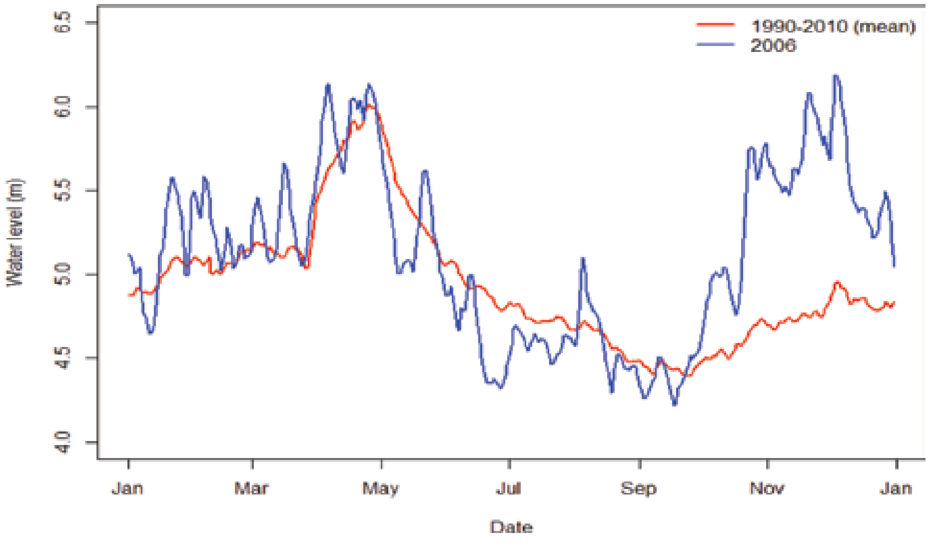

Figure 4. Comparison of daily water levels in the St. Lawrence River measured in 2006 (blue curve) and daily mean values calculated over the period from 1990 to 2010 (red curve) at the Lanoraie station.

(**Table 1** and **Figure 5**). As far as temperature is concerned, it is higher in August (summer) than in May (influence of snowmelt water) and October (effect of fall cooling). In summer, water temperature is roughly twice as high as in the spring or fall due to low water levels (low flow) and the increase in solar energy. TN, for its part, which is mainly derived from farming in Quebec, decreases from spring to fall. In springtime, there is widespread runoff on slopes due to snowmelt, which accounts for the increase in TN concentration in rivers. This concentration decreases in summer as runoff decreases. However, because of the relatively low water levels, the total nitrogen concentration remains higher than in the fall due to limited dilution. In any case, mean TN concentrations during the three seasons are higher than the provincial standard limit value (0.5 mg/L).

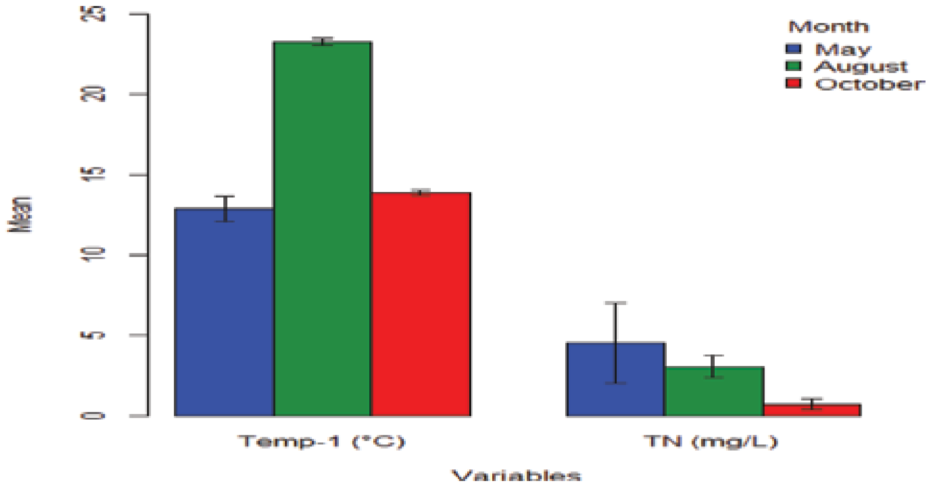

Figure 5. Comparison of seasonal mean values of temperature and TN.

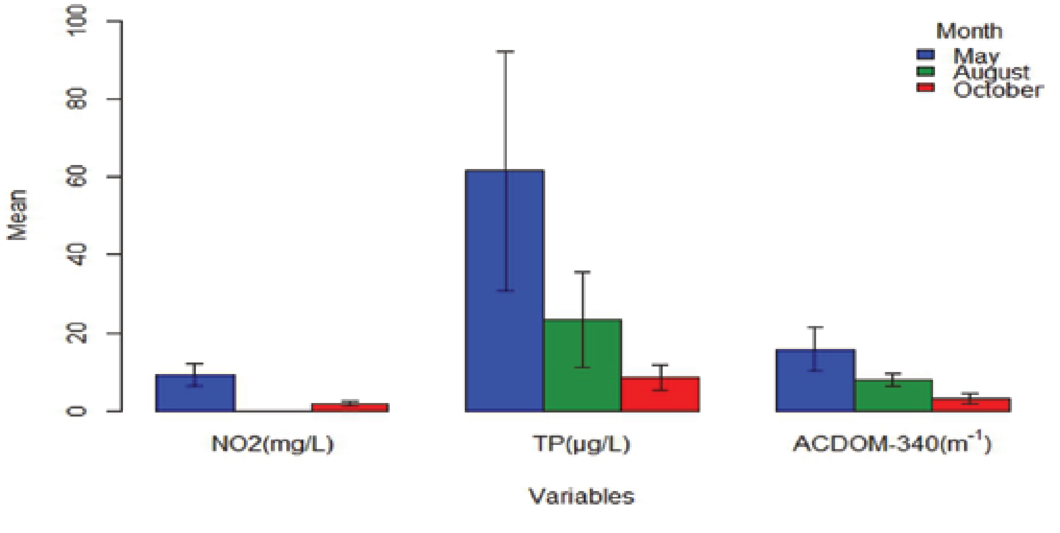

Figure 6. Comparison of seasonal mean values of NO_2, TP and $_{a}CDOM_{340nm}$.

Mean values of six physicochemical variables are significantly different during two seasons. Nitrite (NO_2), total phosphorus (TP), and chromophoric organic matter (aCDOM$_{340nm}$) concentrations are higher in springtime than in the other two seasons (**Figure 6**). This springtime increase is thought to be due to flushing induced by runoff of snowmelt water and resulting in leaching of terrestrial organic and inorganic material. In the case of nitrate (NO_3) and soluble reactive phosphorus (PO_4), their concentrations are higher in summer than in the other two seasons due to limited dilution during the low-flow period and runoff water during summer storm events (**Figure 7**). These two factors can also account for the high values of suspended particles (trans-variable) observed in summer. As for conductivity, its mean value increases markedly in the fall. As far as total phosphorus is concerned, its spring concentration is much higher than the standard limit set by the Ministère de l'Environnement du Québec [34], whereas NO_3 concentrations exceed the standard limit for all three seasons. Mean values of the two other variables (($K_{d(PAR)}$) m^{-1}) and TURB) do not show significant seasonal variations (**Figure 8**). Turbidity values are higher than the provincial standard limit (1NTU) for the three seasons.

4.2. Decadal variability

Mean values of physicochemical variables measured in 2006 were compared with those measured in 1994–1996 by [12] in waters of the St. Lawrence River influenced by the Ottawa River (**Table 2**). Hydrological conditions are similar for the two periods because mean water levels in the St. Lawrence River from May to October are not significantly different. A clear warming of the water is observed between 1994 and 1996 and 2006, as well as a significant increase in nitrite-nitrate concentrations due to climate warming, increased use of nitrogen fertilizers, spreading of solid and liquid manure, as well as effluent releases. In contrast, the amount of phosphate decreased significantly from 1994 to 1996 to 2006 due to its decreasing concentrations in effluents from water treatment plants [34].

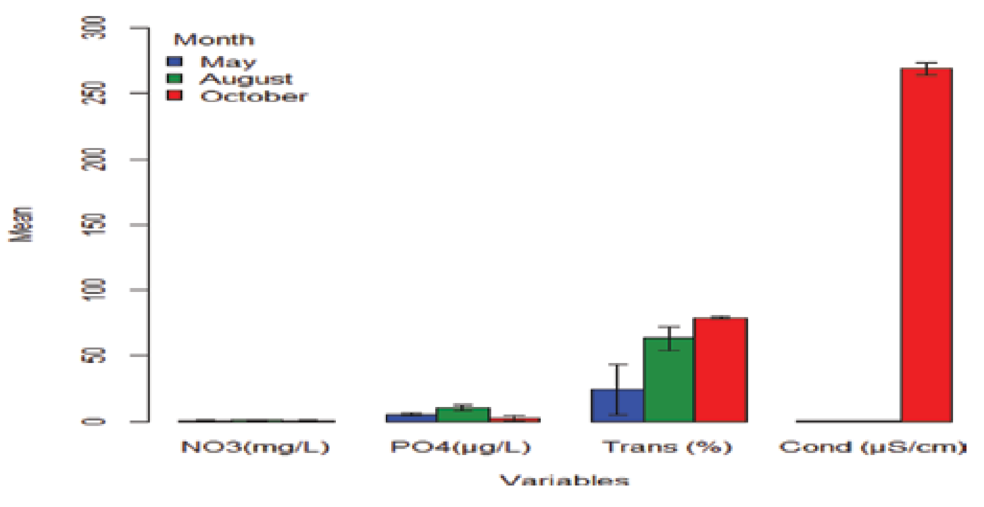

Figure 7. Comparison of seasonal mean values of NO_3, PO_4, transmittance and conductivity.

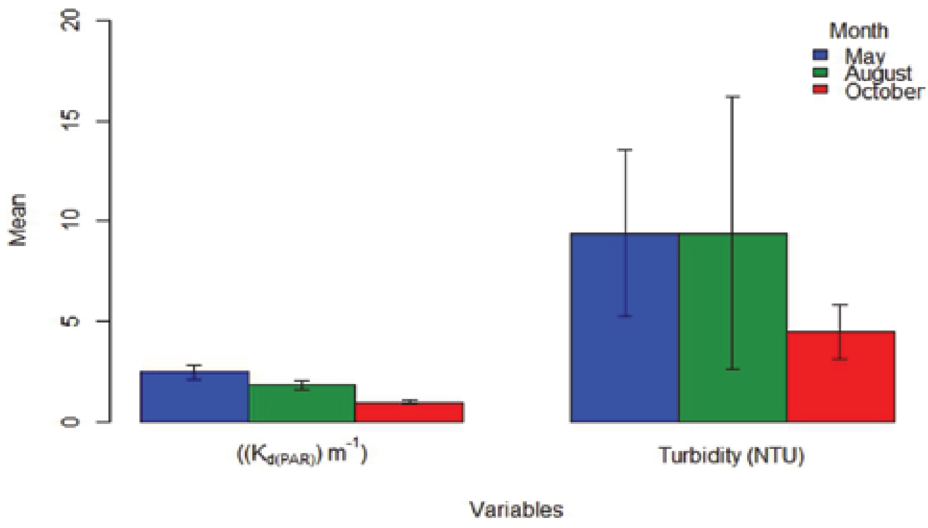

Figure 8. Comparison of seasonal mean values of $K_{d(PAR)}$ and TURB variables.

Variables	1994–1996*	2006
Water level (m)$	4.91 (0.39)	4.78 (0.40)
Temperature (°C)	13.2 (7.9)	16.7 (4.89)
Conductivity (μS/cm)	124 (24)	89.7 (132.46)
Light extinction coefficient (($K_{d(PAR)}$) m^{-1})	1.80 (0.45)	1.75 (0.68)
NO_2-NO_3 (mg/L)	0.35 (0.25)	2.75 (2.13)
PO_4 (mg/L)	0.018 (0.007)	0.0059 (0.0038)

() = standard deviation.*Data published by [12].
$Water levels measured at the Lanoraie station.

Table 2. Comparison of mean concentrations of some physicochemical variables in Ottawa River waters in the St. Lawrence River measured from May to October in 1994–1996 and 2006.

Watershed and water resource management strategies are currently applied in the context of global warming and therefore, cannot be interrupted by the implementation of a new regulation program at the provincial and/or federal level. However, the monitoring of potential negative impacts of global warming on the other components of the river ecosystem (plants, animals, water quality, etc.) would allow the quantification of the environmental damages and the implementation of regulation to protect river ecosystems. Such a regulation would enable the development of appropriate mitigation procedures to minimize dramatic environmental consequences. It is important to note the low number of environmental studies on Québec Rivers and, more specifically, the urgent need for studies devoted to the impacts of global warming on river ecosystems. Without such environmental monitoring, it becomes difficult to predict the evolution of river ecosystems in the context of global warming. The observed increase in nitrites-nitrates in the last 10 years reinforces the need for the Québec Government to develop an efficient management program which would significantly reduce the massive nitrogen fertilizer inputs in agriculture. In addition, this management program should include the respect of legal water quality standards for nitrogen wastes in rural and city areas. These standards already exist but are barely applied.

5. Conclusion

As already pointed out by Hudon [12], flow variations exert a strong influence on the physico-chemical characteristics of Ottawa River waters. This influence was observed in St. Lawrence River waters affected by the Ottawa River. However, this influence does not affect all characteristics in the same way. Depending on this influence, these characteristics may be grouped into three categories. The first category comprises water temperature and total nitrogen, the values of which vary seasonally as a function of water levels. The second category comprises variables that vary significantly over a single season, resulting in marked increases in the spring (NO_2, TP, aCDOM$_{340nm,}$ and suspended particles), summer (NO_3 and PO_4), or fall (Cond). Finally, the third category comprises variables whose mean values do not change significantly as a function of water levels (($K_{d\,(PAR)}$) m^{-1} and TURB).

Comparison of data at the decadal scale revealed a clear warming of waters, a significant increase in nitrite-nitrate concentrations, but a significant decrease in phosphate concentrations. These changes confirm the trend observed since 1979 in many Quebec Rivers [34]. Mean concentrations of these chemical parameters in 2006 were higher than standard limits set for river waters by the Ministère de l'Environnement du Québec as compared to those measured in 1994–1996. In order to assess the ecological integrity of rivers in Québec, there is an urgent need for the implementation of a monitoring program which would allow for the development of solutions to reduce the negative impacts of global warming on the functioning and evolution of river ecosystems. We also recommend reinforcing the strict application of existing water quality laws for nitrogen wastes in rural and city areas.

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Chapter 2

Assessment of Heavy Metals Contamination in Groundwater: A Case Study of the South of Setif Area, East Algeria

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Additional information is available at the end of the chapter

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Abstract

Heavy metals in groundwater were analyzed and their sources and impacts were identified using multivariate statistical tools and risk assessment. Three significant factors were extracted by factor analysis (FA), explaining 75.69% of total variance. These factors were in turn described by the clusters C3, C2 and C1, respectively, resulting from the cluster analysis (CA). Factor analysis and cluster analysis revealed significant anthropogenic contributions and water-rock interaction effects of the metals in groundwater. The mean values of heavy metal evaluation index (HEI) and degree of contamination (C_{deg}) indices indicated that the groundwater samples were contaminated with high degree of pollution by cadmium (Cd) and lead (Pb). The hazard quotients (via ingestion) of Cd and Pb were found to be higher than the safe limits, posing threat to the consumers. However, no risk related to the dermal contact was associated with the measured metal levels.

Keywords: groundwater, heavy metals, multivariate statistical methods, human health risk assessment, recommendation

1. Introduction

In the context of the management of water resources, the identification of heavy metals is a primary importance because of their influence on the quality of groundwater and consequently on the human being.

Guidance contained in this context should relatively take into account national and international watersheds in terms of policy, planning and management, to support a more effective integration of polluted areas [1].

Groundwater is the principal natural water resources for both drinking and agricultural purposes. Nowadays one of the most important environmental issues is groundwater contamination [2, 3]. In areas where population density is high and human use of the land is intensive, groundwater is especially vulnerable. Virtually any activity whereby chemicals or wastes may be released to the environment, either intentionally or accidentally, has the potential to pollute groundwater. When ground water becomes contaminated, it is difficult and expensive to clean up.

Heavy metals are among the major contaminants of groundwater sources [4]. Some of these heavy metals are essential for the growth, development and health of living organisms, whereas others are non-essential as they are indestructible and most of them are categorized as toxic species on organisms [5]. Nonetheless, the toxicity of heavy metals depends on their concentration levels in the environment. With increasing concentrations in environment and decreasing the capacity of soils toward retaining heavy metals, they leach into groundwater and soil solution. Thus, these toxic heavy metals can be accumulated in living tissues and concentrate through the food chain.

The main objectives of this study are: (1) to determine the spatial variation of heavy metals using multivariate statistical techniques, (2) to assess the potential health risk assessment of heavy metals and (3) take preventive and protective measures.

2. Study area and data analysis

The study area is located in the east of Algeria and the south of Setif (**Figure 1**). It is characterized by intensive agricultural and human activities. The climate of this area is semi-arid, with a mean annual temperature and precipitation of 15.2°C and 296 mm/year, respectively [6].

In the current study, 18 wells were collected (**Figure 1**) and 11 parameters (T, pH, EC, Al, Cd, Cu, F, Fe, Pb, Si and Zn) were analyzed using standard procedures [7]. The electrical conductivity (EC), pH and the temperature (T) were measured by multi-parameter WTW (P3 MultiLine pH/LF-SET). The concentrations of heavy metals were determined by Graphite Furnace Atomic Absorption Spectrophotometer (Perkin-Elmer AAnalyst 700).

3. Statistical analysis

The descriptive statistics of heavy metals in the wells of the study area are demonstrated in **Table 1**. Minimum and maximum values of electrical conductivity are 830 and 2730 μS/cm with a mean value of 1451 μS/cm. The measured water temperatures varied from 14 to 18°C with a mean of 16°C. The pH values of the groundwater samples vary from 6.9 to 7.9 with a mean of 7.4 indicating that the waters were generally neutral to slightly alkaline. pH does not show significant positive correlation with any heavy metals, while it shows negative correlation with Fe, Zn and Cd (**Table 2**). This indicates that influence of pH on heavy metals was different in groundwater of the studied area. The mean concentration of Al, Cd, Cu, F, Fe, Pb, Si and Zn was 0.05, 0.066, 0.241, 0.129, 0.255, 0.087, 21.6 and 0.148 mg/l, respectively. Moreover, the mean values of the heavy metal contents in the groundwater follow the decreasing order: Si > Fe > Cu > Zn > F > Pb > Cd > Al.

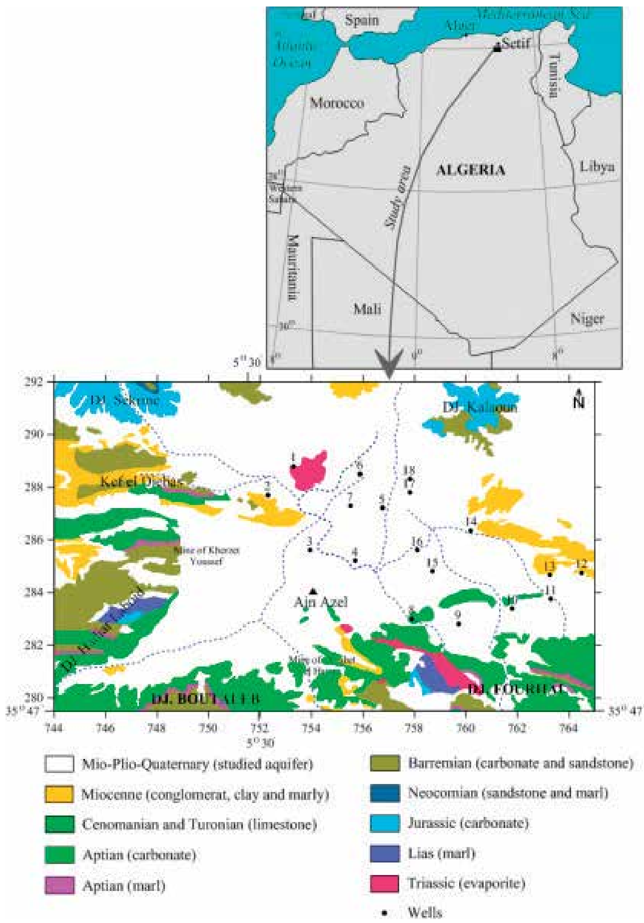

Figure 1. Location of the study area and the samples.

In the present study, factor analysis (FA) and cluster analysis (CA) were used to evaluate the concentrations of heavy elements in groundwater samples.

3.1. Factor analysis

Factor analysis was employed to find and interpret the structure of the underlying data set through a reduced new set of orthogonal (non-correlated) variables (principal components, PCs), arranged in decreasing order of importance. Besides considerable data reduction, PCs can explain the entire multidimensional data set variability without losing much original information. FA with Varimax rotation of standardized component loadings was conducted for extracting and deriving factors, respectively, and those PCs with eigenvalue >1 were retained [8–10]. The distribution manner of individual association of element in groundwater was determined by principal component method (results are shown in **Table 3**). Statistical treatment of these data indicates their association and grouping with three factors explained most of the variability (total variance explained was about 75.69% variance for the groundwater data). The relations among the heavy metals based on the first three factors are illustrated in **Figure 2** in three-dimensional space.

	Min	Max	Mean	SD	CV
EC	830	2730	1451	557	38
T	14	18	16	1.4	8.6
pH	6.9	7.9	7.4	0.3	3.5
Al	0.01	0.09	0.05	0.02	43.69
Cd	0.009	0.165	0.066	0.045	67.646
Cu	0.056	0.43	0.241	0.102	42.248
F	0.017	0.358	0.129	0.111	86.222
Fe	0.055	0.499	0.255	0.116	45.563
Pb	0.017	0.292	0.087	0.069	79.323
Si	12.2	33.3	21.6	7.2	33.2
Zn	0.045	0.276	0.148	0.06	40.466

Remarks: All values are in mg/l except pH, T (°C) and EC (μSiemens/cm). "Min": minimum; "Max": maximum; "SD": standard deviation; "CV" (in %): coefficient of variation.

Table 1. Statistical summary of physicochemical parameters in groundwater samples.

The first factor shows 39.92% of total variance with high loading on Al, F, Pb and Si. These metals were predominantly contributed by the water-rock interaction effects and anthropogenic sources. Aluminum was the most abundant element found in the earth's crust [11] and from the result obtained from its analysis, the minimum concentration of aluminum detected in the groundwater samples is 0.01 mg/l with the maximum concentration being 0.09 mg/l. All samples exceeded the desirable limit of Al for drinking water (0.03 mg/l)

	EC	T	pH	Pb	Fe	Zn	Cu	Cd	Si	F	Al
EC	1										
T	−0.36	1									
pH	0.33	−0.54	1								
Pb	0.32	0.27	0.15	1							
Fe	−0.46	0.19	−0.42	−0.05	1						
Zn	0.20	0.31	−0.29	0.54	−0.08	1					
Cu	0.04	0.12	0.27	0.50	−0.02	0.31	1				
Cd	0.25	0.04	−0.17	0.23	0.37	0.41	0.04	1			
Si	0.43	0.06	0.29	0.26	−0.37	0.06	0.49	−0.03	1		
F	0.78	−0.05	0.40	0.59	−0.49	0.26	0.28	−0.05	0.41	1	
Al	0.72	0.08	0.16	0.44	−0.48	0.28	0.15	0.03	0.36	0.87	1

Table 2. Pearson's correlations matrix for the physicochemical parameters.

Component	Eigen values		
	Total	% of variance	Cumulative %
1	**3.19**	**39.92**	**39.92**
2	**1.77**	**22.08**	**62.00**
3	**1.10**	**13.70**	**75.69**
4	0.69	8.57	84.26
5	0.63	7.89	92.16
6	0.30	3.73	95.89
7	0.24	2.97	98.87
8	0.09	1.13	100.00

Variables	Component			Communalities
	1	2	3	
Pb	−0.74	0.42	0.02	0.64
Fe	0.50	0.66	0.15	0.53
Zn	−0.52	0.58	−0.22	0.48
Cu	−0.55	0.28	0.69	0.47
Cd	−0.08	0.78	−0.24	0.39
Si	−0.61	−0.21	0.53	0.44
F	−0.88	−0.22	−0.23	0.85
Al	−0.81	−0.22	−0.38	0.79

Table 3. Factor analysis of groundwater data. The significant factors (>1) are shown in bold.

except sample 10, but none of the groundwater samples contained Al above the specified maximum contaminant level (0.2 mg/l) [12]. The ranges of fluoride are 0.017–0.358 mg/l. Thus, F concentrations are relatively low in the groundwater (<1.5 mg/l). The concentration of the lead in the groundwater samples ranges from 0.017 to 0.292 mg/l. The groundwater quality standard of lead desirable and maximum permissible limit (WHO) is 0.01 mg/l. All of the groundwater samples are exceeding then WHO desirable and maximum permissible limit of Pb. The concentration of Si in the samples varies from 12.2 to 33.3 mg/l with a mean value of 21.6 mg/l.

The second factor exhibits 22.08% of the total variance with positive loading on Cd, Fe and Zn. The concentration of the cadmium in the water samples varies from 0.009 to 0.165 mg/l with a mean of 0.066 mg/l. The groundwater quality standard of cadmium desirable and maximum permissible limit is 0.003 mg/l. All samples are exceeding then desirable limit of Cd. The concentration of iron ranges from 0.055 to 0.499 mg/l. The concentrations of Fe in many of the samples are higher than the WHO permitted limit of 0.3 mg/l [12] and the percent samples above the limit is 39%. The concentration of the zinc ranges from 0.045 to 0.276 mg/l. The groundwater quality standard of zinc desirable limit is 3 mg/l and maximum permissible limit is 10 mg/l, and all samples are lower than the desirable limit [12].

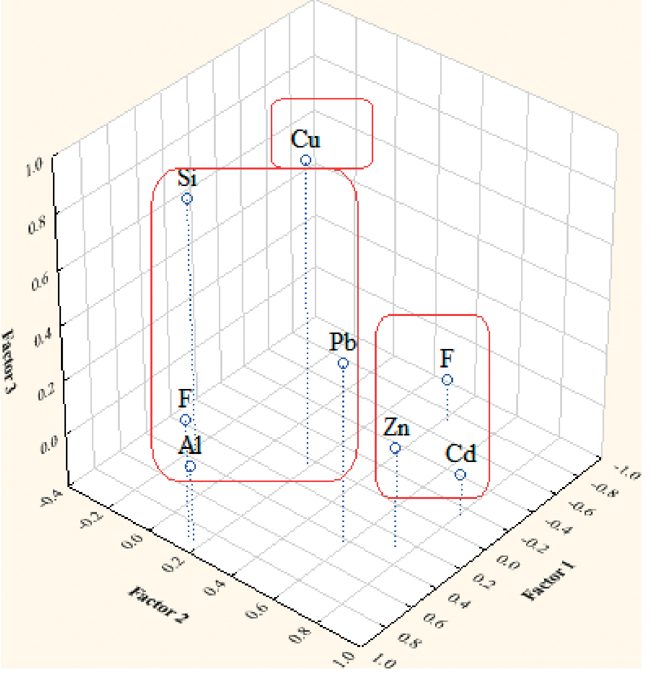

Figure 2. FA results in the three-dimensional space: plot of loading of the first three factors.

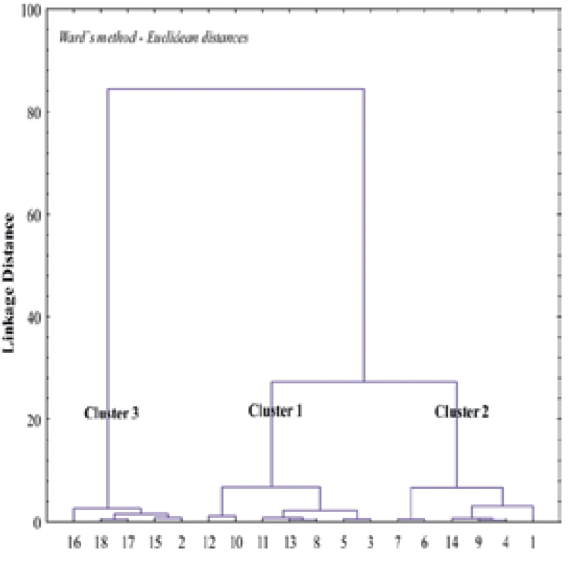

Figure 3. Hierarchical cluster results or dendrogram obtained by CA of the groundwater samples.

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	Cluster 1					Cluster 2					Cluster 3				
	Min	**Max**	**Mean**	**SD**	**CV**	**Min**	**Max**	**Mean**	**SD**	**CV**	**Min**	**Max**	**Mean**	**SD**	**CV**
EC	950	1540	1164	188	16	830	2730	1463	747	51	1340	2530	1836	489	27
T	14.0	18.0	15.6	1.5	9.7	14.0	17.5	16.6	1.3	7.7	14.0	17.0	15.9	1.3	8.4
pH	7.2	7.8	7.5	0.2	3.1	6.9	7.4	7.2	0.2	2.4	7.3	7.9	7.6	0.2	3.2
Al	0.010	0.060	0.037	0.015	40.278	0.030	0.090	0.057	0.023	41.260	0.040	0.090	0.062	0.023	36.780
Cd	0.016	0.165	0.063	0.051	81.045	0.037	0.125	0.076	0.032	41.771	0.009	0.152	0.060	0.057	94.821
Cu	0.056	0.364	0.219	0.097	44.034	0.089	0.311	0.196	0.086	43.942	0.213	0.430	0.326	0.089	27.271
F	0.031	0.128	0.073	0.033	45.940	0.031	0.358	0.133	0.126	94.271	0.017	0.339	0.203	0.137	67.502
Fe	0.188	0.373	0.278	0.066	23.576	0.182	0.499	0.304	0.124	40.596	0.055	0.378	0.164	0.130	79.412
Pb	0.027	0.101	0.058	0.025	42.274	0.029	0.292	0.102	0.096	94.334	0.017	0.193	0.109	0.073	67.210
Si	12.20	16.70	14.89	1.61	10.80	18.20	23.10	20.85	1.81	8.67	30.60	33.30	31.78	1.02	3.20
Zn	0.045	0.190	0.133	0.059	44.492	0.089	0.238	0.160	0.056	35.082	0.087	0.276	0.154	0.073	47.516

Table 4. Statistical summary of physicochemical parameters in the three clusters.

The third factor exhibits 13.7% of the total variance with positive loading on Cu. The concentration of the copper varies from 0.056 to 0.43 mg/l. The groundwater quality standard of copper maximum permissible limit is 2 mg/l. All groundwater samples are less then maximum permissible level of Cu [12].

3.2. Cluster analysis

Cluster analysis (CA) was applied to group objects (cases) into categories or clusters on the basis of similarities within a cluster and dissimilarities between different clusters with respect to distance between objects [13, 14]. Hierarchical agglomerative cluster analysis was performed on the normalized data set using Euclidean distances as a measure of similarity and Ward's method to obtain dendrograms. Three main clusters can be distinguished in the dendrogram shown in **Figure 3**. **Table 4** shows that the increases of electrical conductivity from the first cluster to the last cluster. Cluster analysis confirmed and completed the results obtained by factor analysis.

The first cluster was composed of the wells 3, 5, 8, 10, 11, 12 and 13, and concerns 39% of the total water samples. The mean of electrical conductivity for this cluster is 1164 μS/cm, which presented low concentrations of all heavy metals compared with others clusters (**Figure 4(a)** and **(h)**).

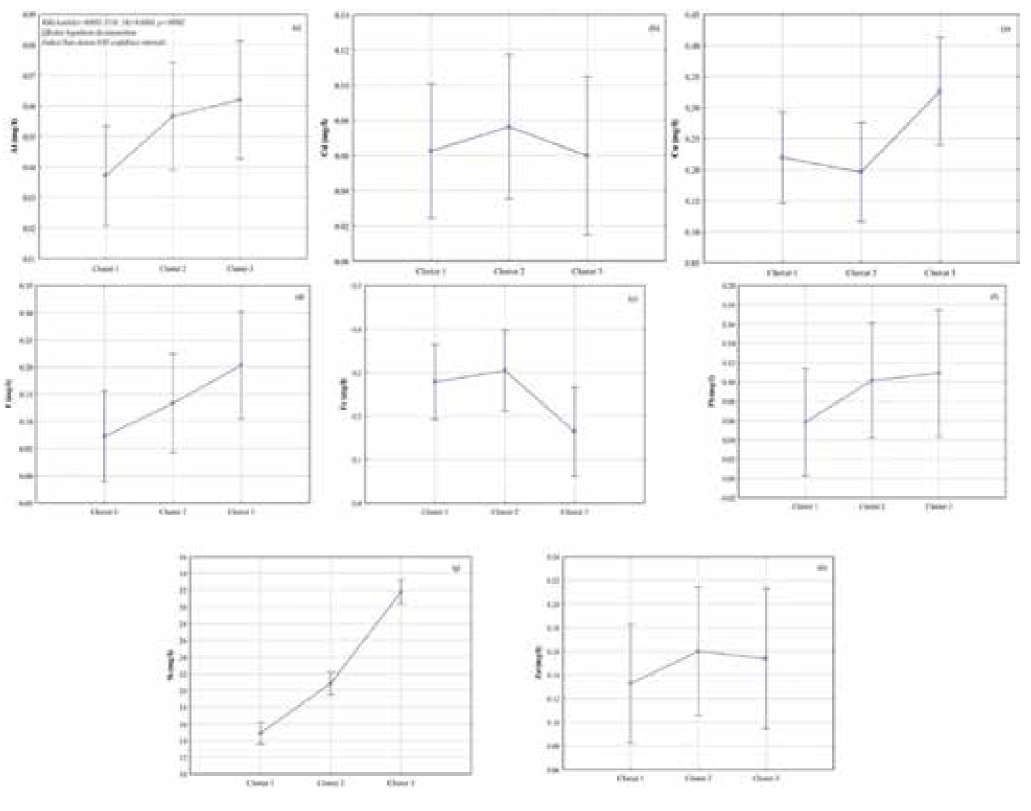

Figure 4. Plot of heavy metals in the three clusters.

The second cluster was represented by the wells 1, 4, 7, 9 and 14, and it occupies 33% of the total water samples (mean EC = 1463 μS/cm). This cluster included samples with the highest concentrations of Cd (0.076 mg/l), Fe (0.304 mg/l) and Zn (0.160 mg/l) (**Figure 4(b)**, **(e)**, and **(h)**).

The third cluster was included samples 2, 15, 16, 17 and 18 (28%), where the mean of EC is 1836 μS/cm. In this cluster, the samples were presented the highest concentrations of Al (0.062 mg/l), Cu (0.326 mg/l), F (0.203 mg/l), Pb (0.109 mg/l) and Si (31.78 mg/l) (**Figure 4(a)**, **(c)**, **(d)**, **(f)**, and **(g)**).

4. Pollution evaluation indices

The degree of pollution in groundwater samples were assessed employing two methods; degree of contamination (C_{deg}) and heavy metal evaluation index (HEI) as reported in the literature [15, 16].

The quality of groundwater was evaluated by calculating contamination index (C_{deg}). The degree of contamination is used as a reference of estimating the extent of metal pollution [17]. This index may be classified into three categories as follows: low (C_{deg} < 1), medium (C_{deg} = 1–3) and high (C_{deg} > 3) [15, 18, 19]. The contamination index was computed from the following equation:

$$C_{\deg} = \sum_{i=1}^{n} C_{fi} \tag{1}$$

$$C_{fi} = \frac{C_{Ai}}{C_{Ni}} - 1 \tag{2}$$

where, "C_{fi}" is contamination factor for the *i*th component, "C_{Ai}" is analytical value for the *i*th component, and "C_{Ni}" is upper permissible concentration of the *i*th component (*N* denotes the "normative value").

The heavy metal evaluation index gives an overall quality of groundwater with respect to heavy metals [19]. This index was computed using the relationship:

$$HEI = \sum_{i=1}^{n} \frac{H_C}{H_{MAC}} \tag{3}$$

where, "H_C" and "H_{MAC}" are the measured value and maximum admissible concentration (MAC) of the *i*th parameter, respectively.

The estimated pollution evaluation indices for the selected heavy metals in the three clusters are shown in **Table 5**. In the first cluster, mean values of HEI and C_{deg} indices were observed to be 29 and 22 (**Table 5**), respectively, which indicated that the water samples of this cluster were contaminated with low degree of pollution by heavy metals, especially Cd and Pb [19]. The mean values of HEI and C_{deg} of the second cluster and the last cluster were respectively

		Cluster 1			Cluster 2			Cluster 3		
	MAC	Mean	HEI	C_{deg}	Mean	HEI	C_{deg}	Mean	HEI	C_{deg}
Al	30	37	1.2	0.2	57	1.9	0.9	62	2.1	1.1
Cd	3	63	21	20	76	25.3	24.3	60	20	19
Cu	2000	219	0.1	−0.9	196	0.1	−0.9	326	0.2	−0.8
F	1500	73	0.05	−0.95	133	0.1	−0.9	203	0.1	−0.9
Fe	300	278	0.9	−0.1	304	1	0	164	0.5	−0.5
Pb	10	58	5.8	4.8	102	10.2	9.2	109	10.9	9.9
Si	—	14,890	—	—	20,850	—	—	31,780	—	—
Zn	3000	133	0.04	−0.96	160	0.05	−0.95	154	0.05	−0.95
∑ HEI/C_{deg}			29	22		39	32		34	27

MAC: maximum admissible concentrations.

Table 5. Description of pollution evaluation indices for selected heavy metals (μg/l) in groundwater samples.

39, 32, 34 and 27 (**Table 5**), revealing high level of pollution with Al, Cd and Pb. Overall, relatively higher heavy metals pollution is observed in the water samples of the second and third cluster than the first cluster.

5. Human health risk assessment

Human health risk assessment was defined as the processes of estimating the probability of occurrence of an event and the probable magnitude of adverse health effects over a specified time period [20, 21]. Exposure of human beings to the metals could occur via three main pathways including direct ingestion, inhalation and dermal absorption through skin; however, ingestion and dermal absorption are common routes for water exposure [22–25].

The numeric expressions for risk assessment have been obtained from USEPA Risk Assessment Guidance for Superfund (RAGS) methodology [22].

$$Exp_{ing} = \frac{C_{water} \times IR \times EF \times ED}{BW \times AT} \tag{4}$$

$$Exp_{derm} = \frac{C_{water} \times SA \times K_p \times ET \times EF \times ED \times CF}{BW \times AT} \tag{5}$$

where, Exp_{ing}: exposure dose through ingestion of water (μg/(kg day)); Exp_{derm}: exposure dose through dermal absorption (μg/(kg day)); C_{water}: concentration of metals estimated in groundwater (μg/l); IR: ingestion rate (2.2 l/day); EF: exposure frequency (365 days/year); ED: exposure duration (30 years); BW: average body weight (70 kg); AT: averaging time (25,550 days); SA: exposed skin area (18,000 cm^2); ET: exposure time (0.58 h/day); CF: unit conversion factor

(0.001 l/cm^3); and K_p: dermal permeability coefficient. These parameter values are taken from reference values or pooled from the statistical data of local population [23, 24].

The characterization of non-carcinogenic risks such as hazard quotients (HQ) and hazard index (HI) is carried out using USEPA guidelines [22, 23]:

$$HQ_{ing/derm} = \frac{Exp_{ing/derm}}{RfD_{ing/derm}} \quad (6)$$

$$HI_{ing/derm} = \sum_{i=1}^{n} HQ_{ing/derm} \quad (7)$$

where, $HQ_{ing/derm}$: Hazard quotient via ingestion/dermal route (unitless); $HI_{ing/derm}$: Hazard index via ingestion/dermal route (unitless); and $RfD_{ing/derm}$: ingestion/dermal reference dose (μg/kg/day).

It is generally accepted that HI below1 is considered to mean no significant risk of non-carcinogenic effects, and if the value of cancer risk is between 10^{-4} and 10^{-6}, it is believed that the carcinogenic risk is acceptable [26, 27].

			Cluster 1		**Cluster 2**		**Cluster 3**	
	RfD_{ing}	**RfD_{derm}**	**Exp_{ing}**	**Exp_{derm}**	**Exp_{ing}**	**Exp_{derm}**	**Exp_{ing}**	**Exp_{derm}**
Al	1000	200	1.163	2.36E−03	1.791	3.64E−03	1.949	3.96E−03
Cd	0.5	0.025	1.980	4.03E−03	2.389	4.86E−03	1.886	3.84E−03
Cu	40	8	6.883	1.40E−02	6.160	1.25E−02	10.246	2.08E−02
F	60	60	2.294	4.67E−03	4.180	8.50E−03	6.380	1.30E−02
Fe	700	140	8.737	1.78E−02	9.554	1.94E−02	5.154	1.05E−02
Pb	1.4	0.42	1.823	1.48E−03	3.206	2.61E−03	3.426	2.79E−03
Zn	300	60	4.180	5.10E−03	5.029	6.14E−03	4.840	5.91E−03
			Cluster 1		**Cluster 2**		**Cluster 3**	
			HQ_{ing}	**HQ_{derm}**	**HQ_{ing}**	**HQ_{derm}**	**HQ_{ing}**	**HQ_{derm}**
Al			1.16E−03	1.18E−05	1.79E−03	1.82E−05	1.95E−03	1.98E−05
Cd			3.96E+00	1.61E−01	4.78E+00	1.94E−01	3.77E+00	1.53E−01
Cu			1.72E−01	1.75E−03	1.54E−01	1.57E−03	2.56E−01	2.60E−03
F			3.82E−02	7.78E−05	6.97E−02	1.42E−04	1.06E−01	2.16E−04
Fe			1.25E−02	1.27E−04	1.36E−02	1.39E−04	7.36E−03	7.49E−05
Pb			1.30E+00	3.53E−03	2.29E+00	6.21E−03	2.45E+00	6.64E−03
Zn			1.39E−02	8.50E−05	1.68E−02	1.02E−04	1.61E−02	9.84E−05
$\sum HI_{ing/derm}$			5.50	0.17	7.32	0.2	6.61	0.16

Table 6. Summary of the health risk assessment for selected metals through ingestion pathway and dermal absorption in water samples.

The health risk assessment parameters for the selected heavy metals in the groundwater samples of the three clusters via oral and dermal routes were described in **Table 6**. In the three clusters, the estimated mean levels of Exp_{ing} and Exp_{derm} in the water samples are observed in the order of Fe > Cu > Zn > F > Pb > Cd > Al and Fe > Cu > F > Zn > Cd > Al > Pb, respectively. The results indicated that Fe, Cu, Zn and F are the major contributors to the ingestion and dermal exposures to the inhabitants, while Cd, Al and Pb are the least participants. Among the selected metals, Cd and Pb ($HQ_{ing} > 1$) posed adverse health risks and potential non-carcinogenic health risks to the inhabitants, while rest of the metals caused little or no adverse effects to the residents via ingestion route. However, the mean levels of HQ_{derm} for the selected metals are found to be lower than unity, indicating that the metals would not pose any adverse effect and non-carcinogenic health risk to the consumers via dermal contact.

Hazard index via ingestion intake (HI_{ing}) and dermal contact (HI_{derm}) are computed to assess the overall non-carcinogenic risk posed by selected metals via ingestion and dermal contact of water as a whole. Among the selected metals, Cd and Pb contributed the most to the mean value of HI_{ing} (6.48), suggesting that these metals deserved serious health concern via ingestion path. However, the mean value of HI_{derm} (0.18) is found to be less than unity, demonstrating that the selected metals posed little or no hazard to residents through dermal contact. Since the largest contributors to chronic non-carcinogenic risks were Cd and Pb in the present investigation, therefore, special attention should be paid to Cd and Pb management in the studied area.

6. Conclusion

In this study, the mean concentrations of heavy metals in groundwater sources in decreasing order was as follows: Si > Fe > Cu > Zn > F > Pb > Cd > Al. Factor analysis method identified three factors responsible for data structure explaining 75.69% of total variance in groundwater. Three major water clusters resulted from the cluster analysis. CA confirmed and completed the results obtained by FA. The mean values of HEI and C_{deg} indices indicated that the water samples of the first cluster were contaminated with low degree of pollution by heavy metals, especially Cd and Pb. The mean values of HEI and C_{deg} of the second and the third cluster revealing high level of contamination with Al, Cd and Pb. Non-carcinogenic health risk assessment was computed to assess the adverse health effects on the population. The hazard quotients (via ingestion) of Cd and Pb were found to be higher than the safe limits, posing threat to the consumers. However, no risk related to the dermal contact was associated with the measured metal levels. In the face of this type of pollution, which has an adverse effect on human health, a number of recommendations and guidelines have been drawn from this study to support the rational use of polluted areas, which are listed as follows:

Recommendations

1. Broad dissemination of the water code, in a vulgarized way, to sensitize citizens who act out of ignorance.
2. A research study and advocate in the field of pollution, because it presents a means of prevention.

3. Landfill and industrial waste discharge in these areas
4. Use of fertilizers in an abusive manner
5. The hydrological process and functions within the basins as well as in the larger terrestrial landscape where they occur must be taken in management.

Orientations

1. At the international level, there are guidelines to promote the inclusion of polluted areas in the management of shared watersheds.
2. At the national level, put in place processes of tight control and cross-sectoral harmonization of policy objectives and to raise awareness of the role and value of polluted areas.
3. The water sector must establish a dynamic political, legislative and institutional environment that takes due account of polluted areas to ensure that the sector has the capacity and information to participate constructively in the protection of polluted areas.

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Chapter 3

Hydro-Geochemical Water Inputs Identification in Glacierized Basin Hydrology

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Additional information is available at the end of the chapter

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Abstract

Mining activities are usually placed in the upper basin regions, especially in developing countries, with economies that strongly rely on natural commodities. Although glaciers do not occupy a large area of these mountain ranges, they deliver vital water for downstream populations. This is especially relevant during drought periods, when winter precipitation is strongly diminished and ice melt becomes relevant. They are also a key resource for highland wetland ecosystems and paradoxically at the same time for the development of mega-mining projects. Regularly, for environmental impact assessments and relevant public consultations, it will be stated that water from glaciers does not constitute an important source within the basin system, even though this has not been accurately quantified. Different water sources, given by spatial, geological, and hydrological features, can be identified using a combination of ionic and isotopic information from water, thus allowing to establish their proportions downstream, where water from different origins is mixed, and also to track their evolution over seasons. This approach should be useful especially for basins with strong pressures for the exploitation and consumption of water in mountainous basins and also with special relevance for basins with little or no knowledge of their water system and reservoirs.

Keywords: mountain basin, mountain hydrology, natural tracers, glaciers, stable isotopes, water sources

1. Introduction

Numerous mountainous regions of the world are being affected by high-impact extractive activities on the environment, such as mining. These projects are mainly placed in developing countries, where large mining conglomerates can often obtain environmental permits more expeditiously than in developed countries. Apart from the discussion of center and periphery geopolitical condition that began this precarious condition throughout the history of these mostly young countries, there is a general lack of knowledge of the environmental characteristics of the mountainous watersheds, which are necessary to contrast the environmental reports made by corporations.

This institutional fragility condition when granting permits is usually driven by a lack of real environmental valuation, with pillars in null or scarce information of the strategic water resources of the basin.

South America is the home to the longest continental mountain range in the world, the Andes. This narrow and high vertebral column that borders along the subcontinental western side rests on seven countries (Venezuela, Colombia, Ecuador, Peru, Bolivia, Chile, and Argentina) ranging from 10° to 55° S, along most of the latitudinal range of the Southern Hemisphere. This natural wall presents a great interference with the planetary winds, producing a redistribution of the precipitation and evapotranspiration that decants in the formation of the most important rainforest of the planet, the Amazon, toward the east of the massif. Inside the Andes, an accumulation of moisture is generated from the Pacific and Atlantic oceans. These precipitations fall mostly as snow and in the highest places accumulate more than it melts year after year. This condition allows the formation of glaciers and high elevation permafrost, with rock glacier development as characteristic permafrost periglacial environment geoforms. Thus, the snow and glaciers of the South American Andes irrigate these hydrologically allochthonous oases, which hold more than 40% of the subcontinent population, accounting for more than 160 million inhabitants.

The importance of being able to understand these systems in an accessible and reliable way not only responds to the pressures exerted by human activities in the glacial and periglacial mountain environments but also relates to climate change processes that combined with the anthropogenic factor produces an enormous pressure over the balance and sustainability of this vital resource. Long-term climate projections do not present an encouraging picture for the Andean region, as they indicate a warming trend and a greater recurrence of droughts in the coming decades [1–3].

In view of this perspective, it is important for the harmonious development of the population to have accurate information of basin water sources. In addition, it is necessary to recognize with spatial precision the different sources of water from the feeding areas within the basin to the areas where it is used by each inhabitant of the territory. All this, interconnected, serves as a basis for establishing development strategies and providing reliable data for decision-makers [4].

In spite of known ice melting relevance in Andean basins, there is a lack of information of its variations of water supply in space and time. Important questions for the management of water in the territory remain unanswered. Some of the main questions are the following: what is the portion of the total water consumed by the inhabitants that is contributed by each water source (snow, glacial, groundwater) in each part of the basin? Productivity activities, such as cultivation or mining, present different water period need along a year, and this question appears: when is each of these sources inputs more or less important for each kind of water consumption in the basin? Because most of water sources in the basin come from high elevation areas, several of these essential questions remain unanswered. The Andean environment is complex and presents extreme fieldwork conditions for the development of accurate measurements [5]. In addition to this, the different methodologies used to measure the quantity of water do not manage to identify the different water sources and their subsequent variation. For instance, the use of satellite imagery allows to estimate the coverage of snow or glaciers, but not how much of its melt contributes to river's streamflow from the melting of snow or ice, respectively. In the same way, gauges can be installed in every proglacial stream and estimate the ice melt contribution, but, besides the complex field-work scenario, the groundwater influence cannot be analyzed in this projection.

The pressure of the large mineral extractive companies usually makes use of and abuse of this kind of information weakness. In mining environmental impact reports, phrases that refer to the insignificance of the water supplied by glaciers or the periglacial environment are usual. Many studies have demonstrated the ice melting relevance for the total streamflow, especially in dry years. These ice giants play a vital role as damp absorbers in warm and arid years, with higher rates of ablation, which can contribute from 67% [6] to 81% of the total summer flow in the Central Andes (31–37°S) [7]. This process is responsible for the droughts in this region to not reach more critical conditions [8].

The relevance of glacial input to river streamflow can be observed in the stable water isotope (e.g., $\delta^{18}O$) composition from the rivers of the Cordillera Frontal geological province (Argentinean Central Andes), in the very dry years of 2011 and 2012 (**Figure 1**). In this example the rivers were receiving different water source inputs but presented the same isotopical composition as rock glaciers (Rgl).

Faced with this lack of information, the present chapter proposes the use of indirect measurement methodologies to identify the contributions of different water sources to the total basin flow. It seeks to be able to know in an accessible and reliable way the significance of the

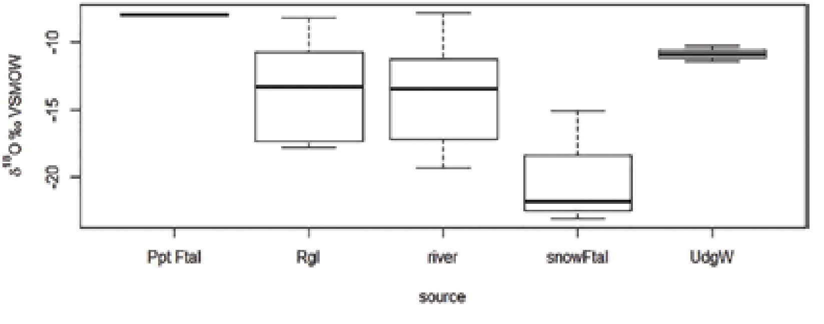

Figure 1. Stable water isotope ($\delta^{18}O$) composition for the different water sources draining the Cordillera Frontal region (32° 56′ S; 69° 22′ W). Ppt Ftal, total precipitation; snowFtal, snowfall samples during storm events; Rgl, rock glaciers; UdgW, groundwaters (Source: personal elaboration).

contribution from each water source and the opportunity to deliver it in space and time using water natural tracers. These are water stable elements with different proportions in each different water source, without significantly changing their properties over time. This property can be analyzed and performs traceability during its journey in the hydrological cycle. In this chapter we will focus on the interpretation and use of two major types of natural water tracers: water stable isotopes and major ions.

This could represent an important tool for policy-makers and the basin's sustainable development in the present and future sociopolitical and climate scenarios.

2. Water source differentiation and quantification using natural tracers

Inner-basin geological differences, in combination with climatic variables and sediment contact time through the basin, provide an ionic and isotope differential composition of natural waters [9–12].

Consequently, this chapter will focus in showing a combination of stable water isotopes and ionic tracer analysis, allowing the readers to identify surface water that originates in different sources like water released from ice bodies, groundwater, rain storms, or snow catchments.

2.1. Ionic tracing

From the universe of water compounds, in this section, we will focus on major ions, which are usually analyzed. Total salinity, measured by electrical conductivity, will also be discussed.

In **Figure 2**, an example from an arid mountain basin (the upper Mendoza River basin) can be observed. The geological map of the area is composed from different geological provinces represented in different mountain ranges, named as Cordillera Principal, Cordillera Frontal, and Precordillera, from west–east direction, respectively. As usually occurs in mountain areas, because of the geological differences from each mountain range, water-draining these geologically different basin areas is expected to present different compositions of minerals and ionic chemistry (**Figures 3** and **4**).

In this case, the samples were taken at different sites in the basin, in 500 cc sterile plastic bottles. For these samples, electrical conductivity and the following major ions, bicarbonate (HCO_3^-), sulfate (SO_4^{-2}), chloride (Cl^-), calcium (Ca^{+2}), magnesium (Mg^{+2}), sodium (Na^+), and potassium (K^+), were analyzed.

As can be observed in **Figure 3**, the geological differences expressed different ionic quantities in the rivers draining the different areas, and the total salinity is like a summary of this process.

For the ionic composition, in a more graphical representation with a Piper diagram (**Figure 4**), a sulfated calcium and magnesium composition for the samples extracted in the Cordillera

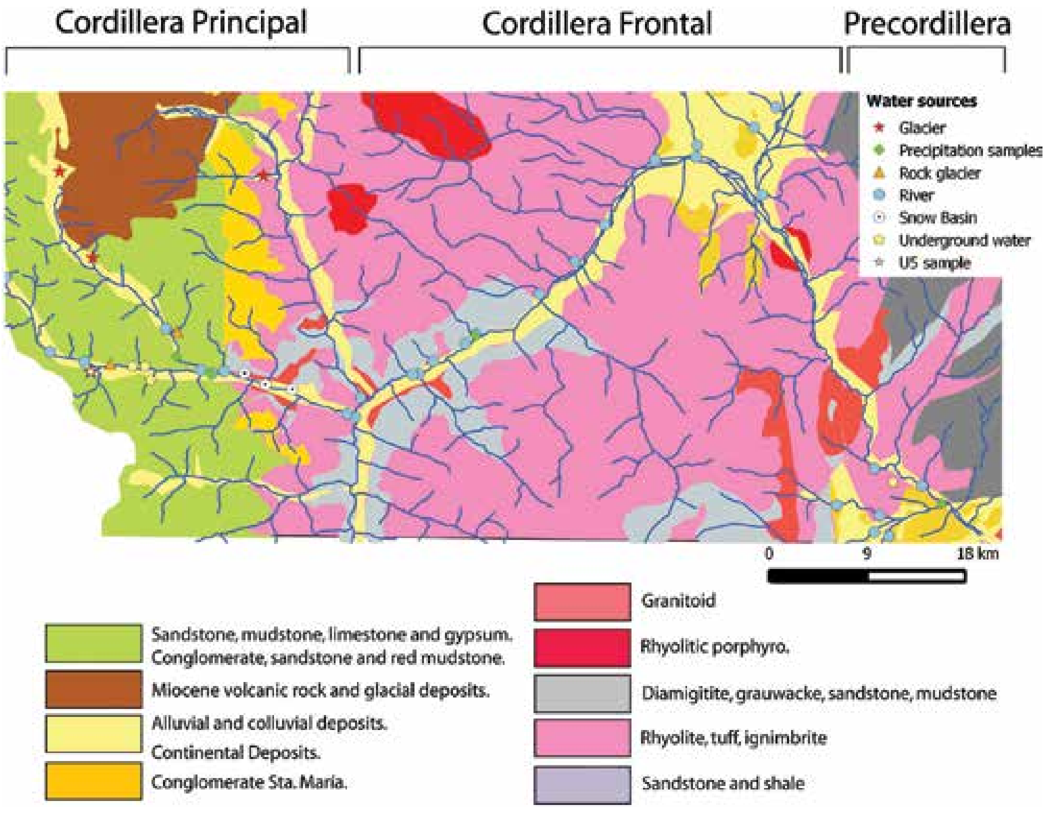

Figure 2. Upper Mendoza River basin (32° 50′ S; 62° 45′ W) geological map (Source: personal elaboration).

Principal and calcium and magnesium bicarbonated for those of the Cordillera Frontal geological province can be seen. Precordillera presents bicarbonated sodium waters mostly. The influence of the petrographic characteristics from the Cordillera Principal, dominating with the presence of gypsum and marking the composition of the Mendoza River waters (mix), which is formed by all the tributaries along the whole studied basin can also be observed.

2.2. Isotopical tracing

Isotopes are atoms of the same element that possess different neutron numbers in its nucleus, presenting equal atomic number but different mass numbers. The differences in mass generate a different behavior in physically reactions. The mass difference between the atomic nuclei is expressed in different reaction rates, because the isotopically heavier molecules have less mobility, resulting in a lower diffusion rate and a lower frequency of collision with other molecules. This derives in a lower possibility of physical reactions, a situation where light molecules react more frequently. This partitioning of isotopes between two substances or two phases of the same substance with different isotopic contents is known as isotopic fractionation [13].

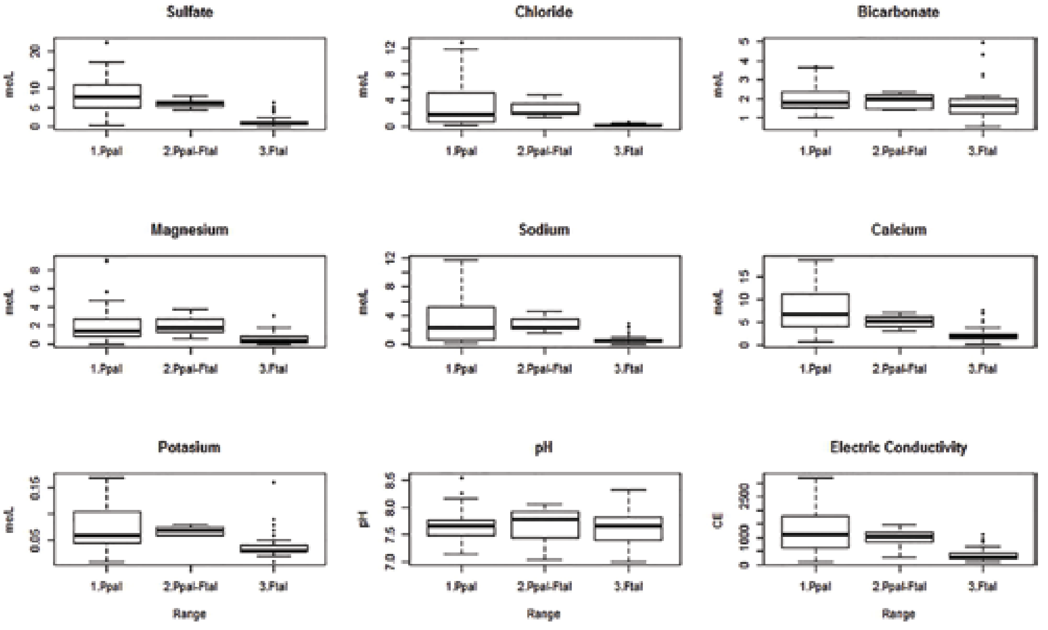

Figure 3. Different mountain ranges' major ions, pH, and electrical conductivity water composition. (1) Ppal, refers to the Cordillera Principal geological province; (2) Ftal, to the Cordillera Frontal, and (3) Ppal-Ftal, to the Mendoza River where the waters incoming from Cordillera Principal and Frontal are mixed (Source: [12]).

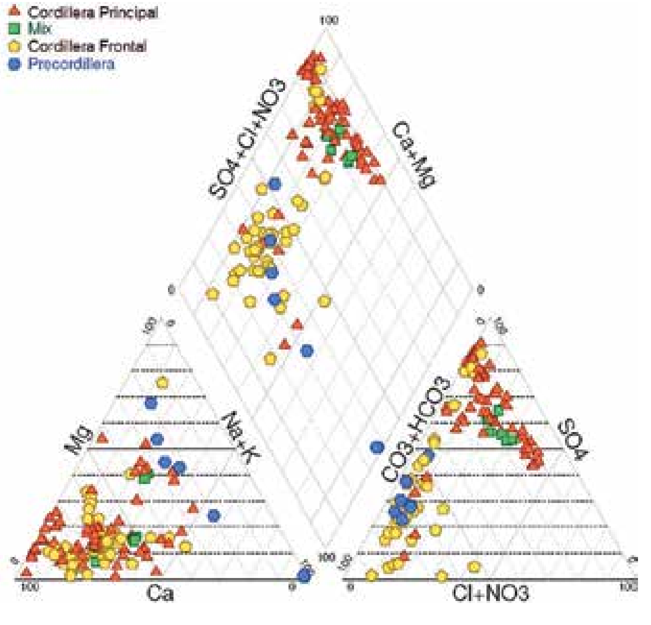

Figure 4. Different geomorphological units within the Mendoza River basin and water ionic composition Piper diagram (Source: [12]).

In order to express the contents of these less abundant isotopes, working standards are used for the measurement of the called δ values. Also, to facilitate interlaboratory comparisons, δ values are scaled to internationally accepted standards. Because water is composed by hydrogen and oxygen, and both present heavy stable isotopes, we will focus on these ones. The hydrogen heavy stable isotopes are deuterium and tritium. Oxygen presents two stable isotopes: ^{18}O and ^{17}O. This chapter will be focused in the more abundant and used: the deuterium ^{2}H and the ^{18}O [14]. The differential composition of the different water sources arises from this explained isotopic partitioning.

The standard commonly used to report the values of $\delta^{18}O$ and $\delta^{2}H$ is the VSMOW (Vienna Standard Mean Ocean Water). Then, the values are expressed in $\delta^{18}O$ y $\delta^{2}H$ ‰, according to Eq. (1):

$$\delta_{VSMOW} = \frac{R_{sample} - R_{VSMOW}}{R_{VSMOW}} * 1000 \quad (1)$$

In this way, when ocean water (which is considered to have an average δ_{VSMOW} value equal to zero) evaporates, it will generate a heavy isotope depletion (which evaporates proportionally less). When moisture is then transported by winds into the continent, water will be discharged as precipitation fractionating preferentially heavy isotopes along its path; therefore, the water vapor will become increasingly depleted on the heavy isotopes. This will leave a characteristic composition in different water sources, depending on the effects that modify this fractionation (continental effect, latitude, altitude, temperature, etc.). The resulting isotopic composition can then be analyzed and its origin and evolution traced [12, 13, 15], as can be observed in **Figure 5**.

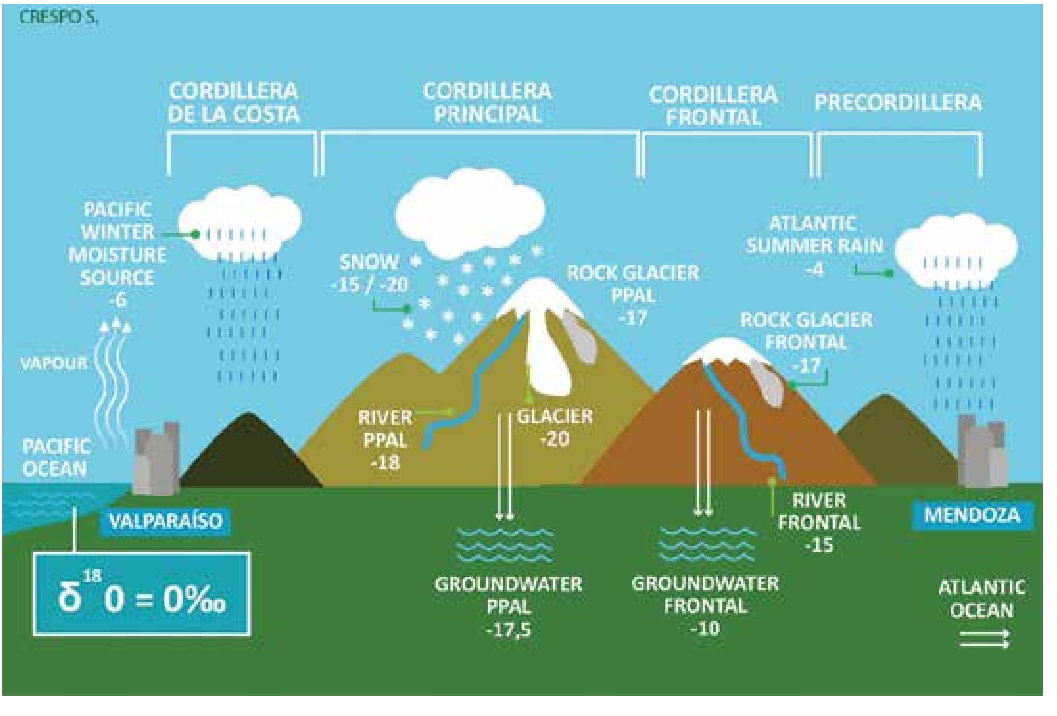

Figure 5. Water $\delta^{18}O$ evolution content in the hydrological cycle (Source: personal elaboration).

In the basis that environmental factors (such as geological and topographical settings, climate, isotope fractionation processes during cloud formation and precipitation) will imprint the stable water isotope composition, researchers have been using this isotopic finger print to identify the water source draining processes to rivers around the world.

Summarizing, isotopic compositions from the different water sources are affected by soil-atmosphere exchange processes, such as precipitation, melting, evaporation, and sublimation [15], which will change according to the altitude, temperature, isotopic composition of the moisture source, and surface characteristics that affect the energy balance of the evaporation processes.

In the case of surface water sampled from the different geomorphological units in a mountain basin (in this case, Cordillera Principal, Cordillera Frontal, and Precordillera mountain ranges), when the co-isotope (δ^2H and δ^{18}O) composition is plotted (**Figure 6**), a significant increase in heavy isotope concentrations as altitude decreases (going east, from the Cordillera Principal to the Precordillera) is clearly observed. Isotopic composition differences between different water sources (glaciers, rock glaciers, groundwater, snow, or rivers) are also observed.

Another useful tool derived from isotopical tracing is the "deuterium excess." Under different conditions than 100% atmospheric humidity, the fractionation rate of hydrogen is higher than oxygen heavy isotopes. This difference in fractionation rates is expressed as the "deuterium excess" and is calculated according to Eq. (2):

$$d = \delta^2 H - 8 * \delta^{18} O \quad (2)$$

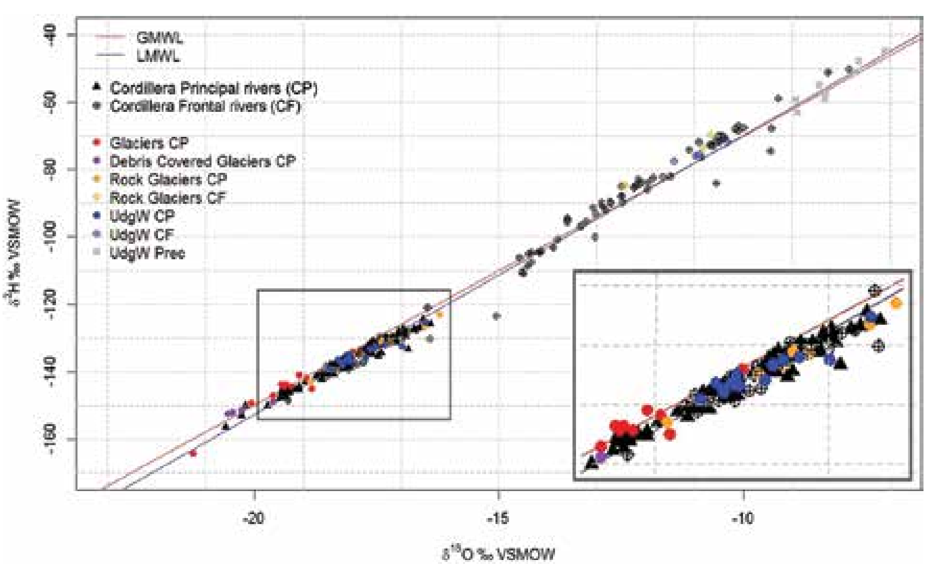

Figure 6. Dispersion of the stable isotope values of water samples analyzed in the Mendoza River basin. The blue line represents the Local Meteoric Water Line (LMWL), following the equation: $\delta^2H = 8.29\ \delta^{18}O + 13.13$; $R^2 = 0.99$. The red line represents the Global Meteoric Water Line, (GMWL) (15) (Source: [12]).

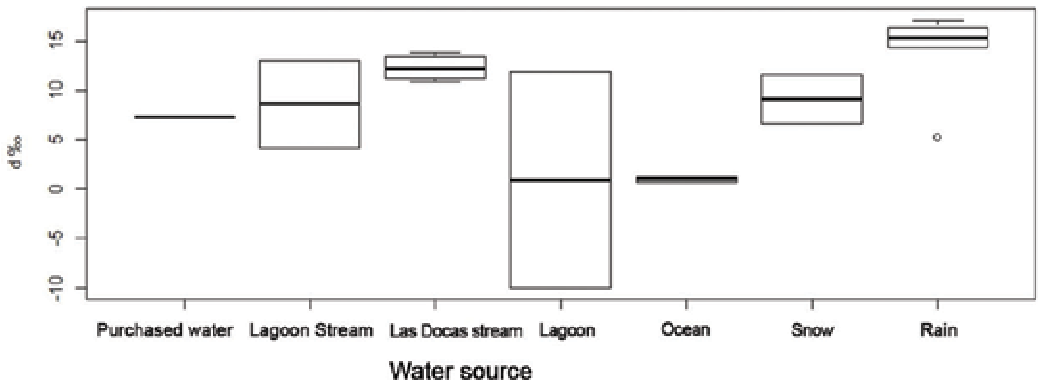

Figure 7. Different water source deuterium excess values in Las Docas beach area, Central Chile (33° 8′ S; 71°42′ W). QLR stream refers to a seasonal stream inside Las Docas region. Lagoon stream refers to the tributary stream feeding the estuarine lagoon (Lagoon) (Source: personal elaboration).

Since $^{18}O/^{16}O$ variations in precipitation were observed [16], Craig [17] described the Global Meteoric Water Line, and Dansgaard [18] introduced the deuterium excess concept, many decades have passed and the stable water isotope applications have developed rather fast. Currently, stable isotopes are widely used by scientists from many different fields to provide information about the origin and geochemical history of water.

This value is very important to determine different evaporation processes, such as by water stagnation and evaporation. In **Figure 7** an example of water sources (in this case in Las Docas region, Central Chile) is presented. Deuterium excess values (d‰) from different streams, rain, and ocean, which fed the estuarine lagoon, show evident differences. The lower deuterium excess values of the lagoon are explained by evaporation processes. The hydrogen isotopes are more affected by the evaporation process than the oxygen heavy isotopes, by the explained mass difference resulting in different fractionation inertias.

Sometimes, two or more water sources cannot be distinguished significantly via δ^2H, $\delta^{18}O$, or ionic determination. In this case, the differential signature can be detected using the deuterium excess value. In **Figure 8**, a graphic example is presented where it was possible to significantly differentiate uncovered glaciers (nr. 1) with snow basins (nrs. 7 and 9) through the differential evaporation condition expressed in the deuterium excess value for each source.

2.3. Combined ionic and isotopic composition analysis

Using the chemical and stable water isotope characterization previously presented, a statistical analysis could be carried out to investigate if any significant differences can be identified and thus to strengthen the information that can be provided in order to identify different water sources. As it was observed for the Mendoza River basin (**Figures 4**, **6**, and **8**), the different tracer composition allows the contribution identification from different geographic origins in space and time, considering the characteristic composition of each type of water source in each subbasin and, from there, estimates the proportion and moment of water delivery in a basin [12].

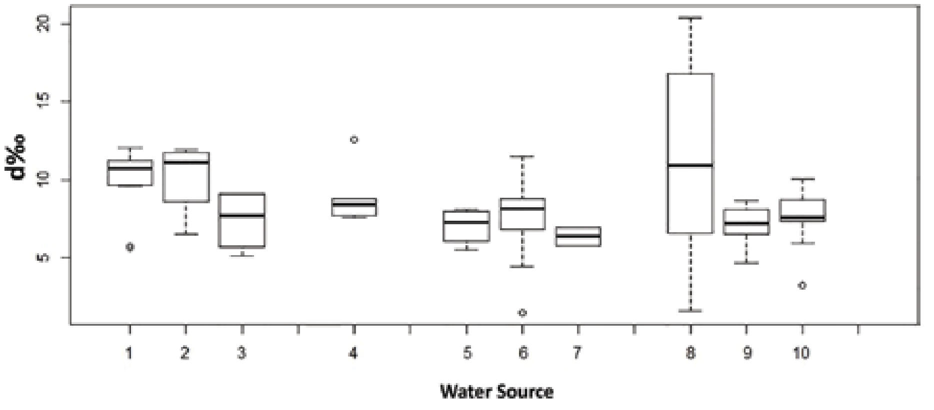

Figure 8. Different water sources (in numbers) deuterium excess values (D‰) in the Cordillera Principal mountain range area, upper Mendoza River basin. (1) glacier, (2) debris-covered glacier, (3) debris-covered glacier and rock glacier, (4) total precipitation, (5) rock glacier, (6) rivers and streams, (7) "Valle Azul" stream in winter and spring, (8) snow, (9) "Los Puquios" stream in winter and spring, (10) groundwater (Source: [4]).

A combination of both, ionic and isotopic compositions, can reveal river behaviors along a year. In this case, a simplification thought a principal components analysis (PCA) can be a useful way. As can be seen in **Figure 9**, the first dimension of a principal component analysis (PCA), related to ion chemistry, separates groundwater from snow and ice bodies. The second dimension, related to stable isotopes, separates the snow and the different types of ice bodies (snow and rock glacier from uncovered or debris-covered glaciers). The temporal evolution of the different rivers along the main dimensions of the PCA shows a movement along the stable isotope axis, which is considerable in summer compared to autumn in several rivers. Saline

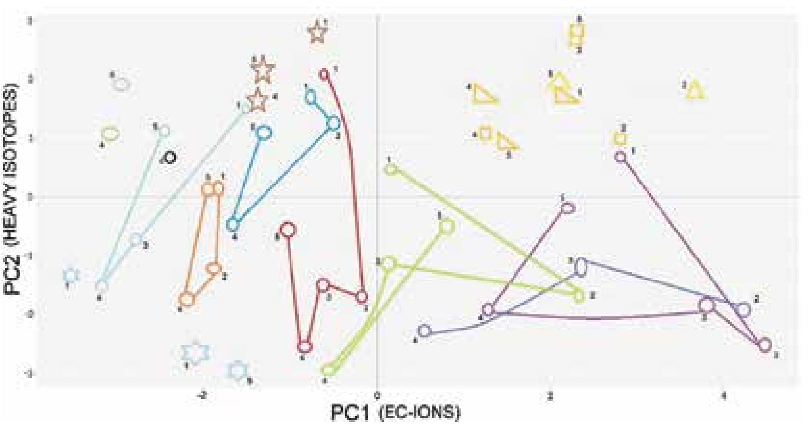

Figure 9. Stable isotopes and salts of water samples from the Mendoza River basin principal components analysis (PCA) plot. The behavior (marked by the dominance of the contribution of glaciers, groundwater, or snow) of the different subbasins that contribute to the Mendoza River (marked by the different rivers with the lines in different colors), throughout the seasons of the year. The number 1 corresponds to summer, 2 autumn, 3 winter, 4 spring, and 5 to the summer of the following year. In the upper left margin is the resulting characteristic of rock glaciers (brown stars) and snow precipitation (green and black circles). In the upper right of the groundwater (yellow rectangles and triangles) and, in the lower left, the characteristic features of glaciers (blue stars) (Source: [12]).

concentration is observed in autumn, indicating the contribution of water with greater contact with sediments (groundwater). The observed changes from autumn to spring are observed in the ion dilution dimension and then again become a predominantly snow contribution in early summer. In this case, it was a temporal lagoon detected (purple circle in **Figure 9**). The water source that had been feeding the lagoon was unknown, because it could be a snowmelt or a groundwater water source origin. As can be observed (**Figure 9**), after the PCA analysis, the snowmelt provenance of the water filling this temporal small lagoon was inferred [12].

2.4. Water source input quantification

In order to quantitatively estimate the relative contributions from each type of water source to a river flow, an end-member mixing analysis (EMMA) [19] could be performed based on the chemical determinations previously explained.

In this way, the equation for proportions *(f)* of river inputs composed by three components (*C:* snow or rock glacier, glacier, and groundwater) requires the use of two tracers (ions and isotopes), and the ratio of each source is calculated according to the following set of equations (Eqs. 3 to 8):

$$1 = f_1 + f_2 + f_2 \tag{3}$$

$$C_1^1 f_1 + C_2^1 f_2 + C_3^1 f_3 = C_t^1 \tag{4}$$

$$C_1^2 f_1 + C_2^2 f_2 + C_3^2 f_3 = C_t^2 \tag{5}$$

where f is the discharge fraction and C is the component concentration. The subscripts refer to the components and superscripts to the tracers.

And, finally

$$f_1 = \frac{(C_t^1 - C_3^1)(C_2^2 - C_3^2) - (C_2^1 - C_3^1)(C_t^2 - C_3^2)}{(C_1^1 - C_3^1)(C_2^2 - C_3^2) - (C_2^1 - C_3^1)(C_1^2 - C_3^2)} \tag{6}$$

$$f^2 = \left(\frac{(C_t^1 - C_3^1)}{(C_2^1 - C_3^1)}\right) - \left(\frac{(C_1^1 - C_3^1)}{(C_2^1 - C_3^1)}\right) f^1 \tag{7}$$

$$f_1 = 1 - f_1 - f_2 \tag{8}$$

For three components and two tracer models, as it was the example, the mixing spaces are defined by the two tracers (e.g., isotopic composition and electrical conductivity). If they are graphed, the three components must form the vertices of a triangle, and all the samples of the river must be framed by the triangle. If this standard is not met, the tracers are not conservative, or there may be contributions from other sources not characterized (**Figure 10**).

In this example, the relative contribution from each water source for the Cuevas River in February 2014 is presented in **Table 1**.

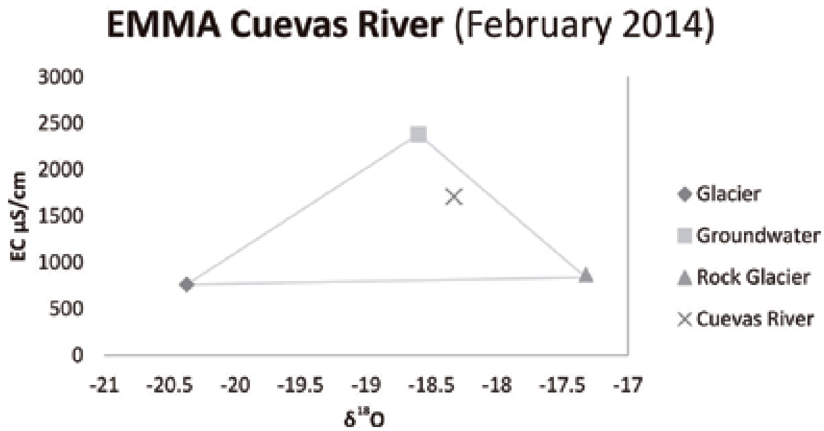

Figure 10. Scatter plot showing the isotopic and average electrical conductivity (EC) compositions for the different water sources that contribute to the Cuevas River in February (Source: [4]).

Water source	Glacier	Groundwater	Rock glacier	Other	Total
Water source contribution (%)	9	56	34	1	100

Table 1. Percentage contribution from different water sources to the Cuevas River along February 2014 (source: [4]).

3. Conclusions

In water management, a lack of knowledge about the natural water source contribution variability in different periods of the year exists, which is critical at any time when it is necessary to maintain the water balance between supply and demand in a certain territory. Within the large basins, there is still a great complexity for the determination of water sources in high elevation areas. This is also a challenge for small basins, where water systems can be even more fragile. The difficulty lies in the fact that in high-altitude areas with different water sources, there are variations in the contribution proportion from each kind of water source, along each season of the year. Among them, we can count the presence of glaciers, snow, total precipitation, wetlands, groundwater, and permafrost, where all can contribute to the runoff and recharge aquifers in territories located in lower areas within the basin. As could be observed in this chapter, using chemical tracing through natural tracers represents a reliable way to distinguish and quantify the different water sources input in a river.

Society is the main target of any water basin analysis, and, based on it, territorial prospecting can make important contributions in the estimation of impacts and in the mitigation infrastructure design. In this context, this chapter focuses on the determination of water sources in high-altitude areas using natural tracers, which can be very useful for the communities that inhabit the basins in mountain areas. The spatial and temporal distribution data of the water supply's main components is fundamental for the hydrological resource use and distribution planning among the basin's different social actors. These tools could be relevant to water supply projections and water demand regulations when analyzing the water source bail in upper basin areas, as a consequence of precipitation reduction and temperature increase in high elevations, which, for example, has resulted in a generalized retreat of the glaciers along the Central Andes [8, 20–22]. It is estimated that these glaciers' fronts and areas' negative variations are largely due to the rise of the 0°C isotherm in the region [23]. Also, when some corporations deny any specific water source contribution relevance, these tools can provide a good exploration analysis to determine their water contribution.

Recently, between 2010 and 2015, the Andes region between 29° and 35°S experienced the longest drought in the instrumental record [3]. This extraordinary event has occurred in the warmest decade of the last 100 years and apparently has no analogies in the last millennium, according to paleoclimatic reconstructions of this area [3]. The long-term climate projections also do not present an encouraging picture for this region of the Andes, since they indicate a tendency to warming and a greater recurrence of droughts in the coming decades [1, 3, 24].

In view of the worrying future perspective that is coming for this region (and others) in terms of its reduction of strategic water resources, it is vital to know in detail the behavior of the different water sources associated with climate variability. In this chapter we have shown the different contribution along time and space from different water sources, which can be key information for the development of reservoir infrastructure and water distribution networks, generation of water supply, and distribution models for different uses, in addition to other adaptation plans aimed at specific sectors of the population.

The use of ionic and isotopic tools, together with traditional hydrological and climatic data, can allow the creation of new information and early warning systems to reduce the risk of droughts and floods, among other applications that will modernize the way we guide decision-making in complex climate dynamic mountain basins. Besides this, extending these tools to other areas of the landscape, such as the foothills, lowlands, and valleys, will be useful to recognize and quantify changes in isotopic signatures in space and time. The knowledge of this water information can be considered analogous to the knowledge of the circulatory system in living organisms, because it is vital to diagnose the functioning and health of the ecosystems that feed on this resource in different basin zones. This information will favor the different water source feature identification from the feeding areas within the basin to the areas where it is used by each inhabitant of the territory.

In summary, the development of new geographic and temporal information systems using chemical and isotopic tools is of fundamental importance for water distribution, flood, and drought damping infrastructure planning scenarios. Interconnected to other environmental parameters, it will serve as a basis to establish development strategies and provide information for decision-making in areas that depend on mountain hydrology and its complex network of water sources that supply the territory.

Acknowledgements

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A. Appendices and nomenclatures

Glacier (discovered and covered): permanent ice body generated on the ground by snow and/or ice recrystallization due to the compaction of its own weight, without or with significant detrital coverage, which is visible for more than 2 consecutive years, with movement evidence or not. Glaciers can have different morphologies.

Groundwater: this term is used here to describe indistinctly (unless clarified) to spring waters and can represent waters of the soil matrix or from deep water and old sources.

Periglacial environment: this term is used to describe the climate and the geomorphic processes of the peripheral areas to the discovered ice and to those distant zones to these also without direct relation with glaciers but with the low temperatures, with permanently frozen soils and even with those zones with short period, seasonal, or daily freezes. In many cases the ice can be trapped and preserved under natural conditions for a long time, thus constituting the decisive element of the cryogenic environment [25].

Permafrost: soil that remains frozen for 2 or more consecutive years.

Rock glacier: frozen debris body and ice with evidences of movement by gravity and permafrost plastic deformation, whose origin is related to the cryogenic processes associated with permanently frozen ground and with underground ice or with ice from uncovered and debris-covered glaciers.

Snow basin: refers to a basin where the snow precipitation is the very major water source.

Total precipitation: refers to the meteoric water precipitated at any state (solid or liquid).

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Chapter 4

Basin Scale Performance of a Distributed Rainfall-Runoff Model Using Uncertainty Modelling Approach in Data Scarce Region

Madaka Harold Tumbo

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.78539

Abstract

Lack of hydrological information of the most basins in Tanzania increase uncertainties in understanding hydrological processes in the basin, and consequently leads to risks decision making related to significant water resources development plans and climate change adaptation. The lack of hydrological information also is coupled with uncertainty related to the predictions of future climate and land use change. Some of the gaps can be filled using rainfall-runoff modeling, which results can be used to generate reliable information to enable decision making and planning for water resources management. This paper discusses the results of applying a semi-distributed rainfall-runoff model which was established for the Little Ruaha Sub-Basin, using the available historical data, with a goal of understanding processes of runoff generation and the inherent uncertainty related to data. Issues of water resources assessment in the basin and approaches used to address them, and some directions for future research are discussed. There are challenges associated with the quality of data for model set-up and understanding of the model structure. Despite these challenges, there remain many opportunities to improve the methods used for water resources assessment and management within the basin.

Keywords: hydrological modeling, uncertainty, rainfall-runoff modeling

1. Introduction

The Soil and Water Assessment Tool (SWAT) is a hydrological simulation tool that is widely used by researchers and postgraduate students in Tanzania. This could be attributed to the free online spatial dataset (elevation, soil, land cover) necessary for setting up SWAT. However, the ease of setting up SWAT using the available information does not mean that the model will give behavioral results. The calibration of hydrological models for water resources assessments is often difficult due to the large numbers of model parameters, and the difficulty increases with the model complexity. Similarly, calibration and uncertainty analysis are a pre-requisite of any hydrological modeling study. Despite, the claimed wide use of SWAT in Tanzania, the whole issue of uncertainty has been ignored, where the uncertainty framework within SWAT is used for the optimization of objective functions only [1]. In this study, SWAT2009 was used to explore the implementation of the uncertainty analysis framework for the meaningful application of the results.

SUFI 2 framework is used for the implementation of uncertainty analysis in this study. The framework was selected because it takes fewer runs in comparison to other calibration procedures tailored for SWAT. According to [2–5] SUFI-2 parameter uncertainty accounts for all sources of uncertainties such as uncertainty in input data, model structure, and parameters. All uncertainties are quantified by a measure referred to as the P-factor, which is the percentage of measured data bracketed by the 95% prediction uncertainty (95PPU) and R-factor which is the measure of the width of the uncertainty band.

The concept behind the uncertainty analysis of the SUFI-2 algorithm is illustrated graphically in **Figure 1**. The diagram illustrates that a single parameter value (black dot) leads to a single model response (**Figure 1a**), while the propagation of the uncertainty in a parameter (shown

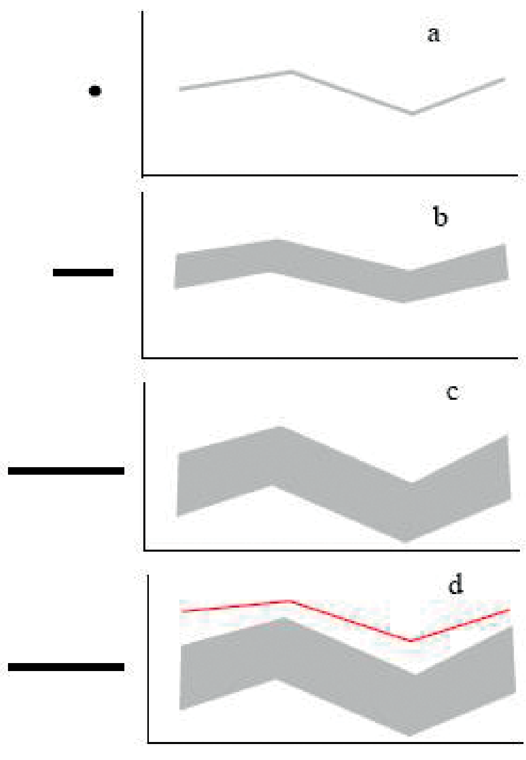


Figure 1. A conceptual illustration of the relationship between parameter uncertainty and prediction uncertainty.

by a line) leads to the 95PPU illustrated by the shaded region in **Figure 1b**. As parameter uncertainty increases, the output uncertainty also increases (**Figure 1c**). SUFI-2 normally begin with a large parameter uncertainty (within a physically meaningful range) to make sure that the observed data falls within the 95PPU, then decreases this uncertainty in steps while monitoring the P-factor and the R-factor. If the initial parameter ranges are equal to the maximum physically meaningful ranges and still cannot find a 95PPU that brackets any or most of the data (**Figure 1d**), then the conceptual model needs to be re-examined [4]. In each step, initial parameter ranges are updated by calculating the sensitivity matrix, an equivalent of a Hessian matrix, followed by the calculation of the covariance matrix, 95% confidence intervals of the parameters, and correlation matrix. Parameters are then updated in such a way that the new ranges are smaller than the previous ranges and are centered on the best simulation. More details on SUFI-2 and its algorithm can be found in Abbaspour et al. [3, 4]. The uncertainty analysis in this study was implemented in the two stages;

1. Assigning initial parameter ranges: the complete physical range of each parameter was used to explore the surface response using Latin Hypercube sampling and to select the initial range for each parameter.
2. Derivation of a reduced parameter range and predictive uncertainty: the procedure identifies a range for each parameter in such a way that upon propagation:
   - The 95% prediction uncertainty (95PPU) between the 2.5th and 97.5th percentiles contain (brackets) a predefined percentage of the measured data, and
   - The average distance between the 2.5th and 97.5th prediction percentiles is less than the standard deviation of the measured data [3, 4].

The model performance was assessed based on the two conditions being fulfilled and a good agreement between the simulated and the observed data for a calibration and validation period. In theory, the P factor values range between 0 and 100%, while the R-factor ranges between 0 and infinity [4]. A P-factor of 1 and R-factor of zero is a simulation that exactly corresponds to measured data. The degree of departure from these numbers is used to judge the strength of calibration. It is possible to achieve a good P-factor at the expense of a larger R-factor; therefore, there should be a balance between the two factors [4]. Other performance measures used are the R^2 and Nash-Sutcliffe (CE) coefficient.

2. Study area

The Little Ruaha basin (**Figure 2**) falls within the African land surface where the infiltration of the topsoil is good, and interflow is an important component of the River discharge. The soils in the upper part are deeply weathered and have a good soil structure. The total area for this sub-catchment is approximately 5200 km^2. The headwaters of the Little Ruaha River (gauging station 1 ka31) originate from a permanent swamp covering an area of approximately 30–50 km^2. The seasonal variation of the runoff is less apparent for the Little Ruaha

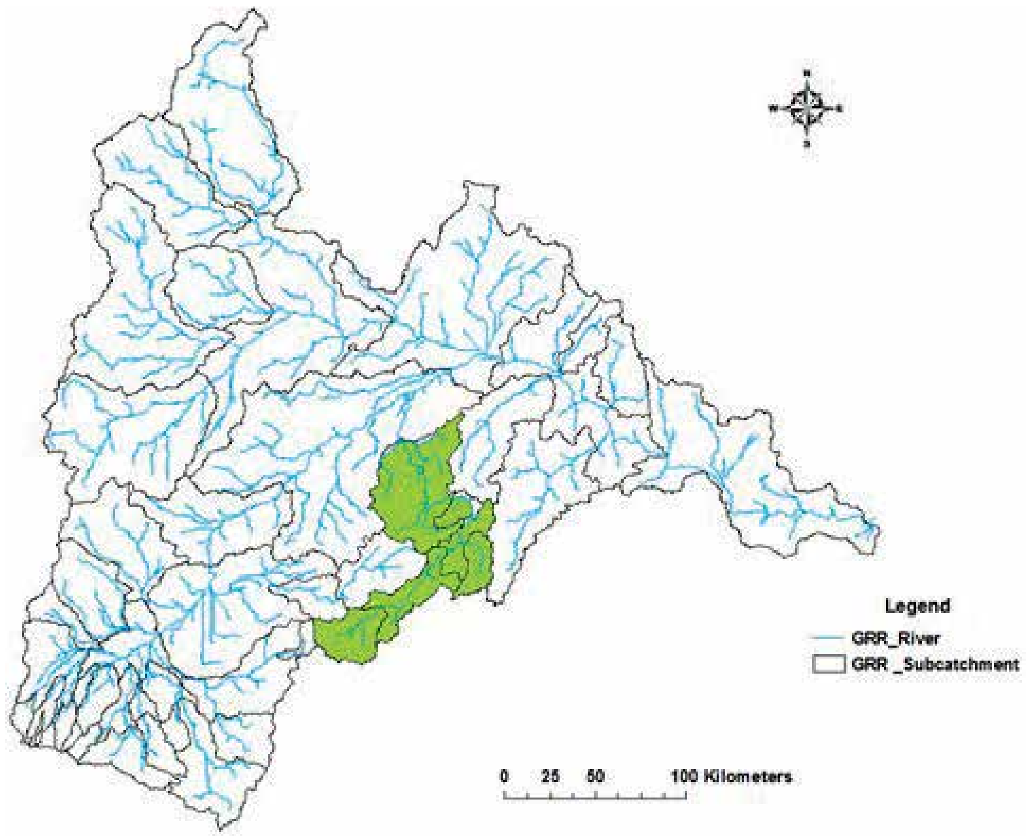


Figure 2. The Great Ruaha River Basin with Little Ruaha River sub-basin (presented in green).

River, due to a considerable infiltration and ground water recharge during the wet season which is favored by relatively high and often less intensive rainfall [6]. The maximum and minimum recorded flows of the River are 775.0 and 2.8 $m^3 s^{-1}$ during March and October, respectively. Estimates of groundwater recharge are discussed in the Water Master Plan for Iringa, Ruvuma, and Mbeya regions [7]. Based on the CCKK report, the base flow component constituted about 80% of the total annual stream flow, which is consistent with the fact that the catchment is characterized by swamps in the headwaters but also, has highly permeable soils. This implies that there is high recharge.

2.1. Geology

The geology of the Little Ruaha basin is mainly covered by the Usagarans System. The system covers the Great Ruaha and Kilombero catchments, in Great Ruaha, the system mostly covers Iringa region where Little Ruaha flows. These are rocks extending N-NE and S-SW of the Archean Tanzania Craton. The rocks formed between (2.1–1.8) Ga striking W-E to SW. Geologists have used different abbreviations for ages (time before present) and duration (amount of time elapsing between two different events). Ages are abbreviated from Latin:

Ga (giga-annum) is a billion years, Ma (mega-annum) is a million years, ka (kilo-annum) is a thousand years. Major rock types in the system are crystalline limestone, graphite schists, and gneiss metamorphosed under amphibolites facies condition due to granitization and migmatization which took place during Pan African tectonothermal event 0.5 Ga which affected the Mozambique mobile belt. The system also contains granulites and granitic intrusions (1.8–1.85) in some parts of Iringa region, volcanic rhyolite lavas, granite gneiss, eclogite, and agglomerates are found in some areas of Kilombero in the Udzungwa Mountains and the Kilombero basins. The volcanic behavior in lower Kilombero is witnessed with high-temperature ground water recorded at monitoring borehole located at Ikule primary school in Ifakara and the volcanic soil. The rock types in the Usagaran system are dominant in Iringa, Mufindi, Njombe, Kilolo, Kilosa and Kilombero districts, which are in Great Ruaha and Kilombero catchments. The rocks are found in a part of Makete district though other parts are affected and dominated by Rungwe volcanic (anorthosites, basalts, peridotites, pyroxenites).

2.2. Soils

The soils in the upper parts are deeply weathered and have good soil structure, but the relatively high rainfall has resulted in heavily leached soils with low fertility. The soils in the lower part Agro-ecological zone 8 are moderately fertile red clays and loams although sandy soils with low fertility are quite common.

2.3. Topography

The basin is characterized by flat to undulating topography and inselbergs are common. While humid forest remnant covers the upper part of the zone, Acacia scrubland is more typical in the lower drier areas. The characteristic features of the basin, apart from the Rift Valley system, are the surrounding uplifted and warped plateaus. Covering nearly 90% of the total Iringa and Mbeya regions, the plateaus represent by far the most common land form. Fault-lines and erosion scarps separate them and are the result of steady erosion that has taken place since the Late Jurassic period.

2.4. Climate

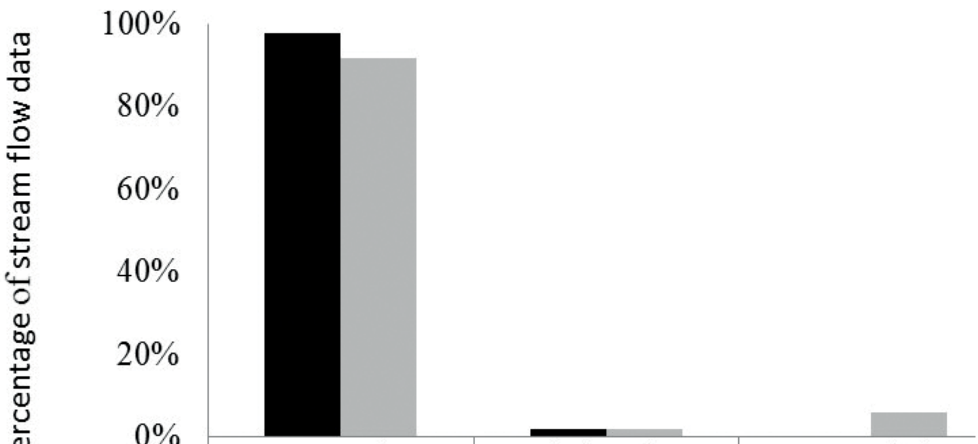
Rainfall is highest in the south–eastern part of the basin about 1200–1400 mm in the steep upper catchments areas, decreasing with altitude to 800–1000 mm in the middle part of the catchment which has undulating topography, whereas the lower parts of the catchments south-west of Iringa only receive about 700 mm. The rainfall is unimodal. Rain normally starts in November/December and ends in April/May. In the upper catchment areas rainy season often continues into the beginning of June for example in 1994 the rainy season finished in Iringa by mid-April whereas it was still raining in the upper part of the basin until the beginning of June.

2.5. Land use and farms

Most of the population in this catchment depends on agricultural production, and the farming systems which evolved in this zone are predominantly smallholder with the average cultivated area varying from 1 to 2 ha per household. Large-scale farming is limited a few numbers of individuals and companies (often parastatals). Maize is the dominant crop in most of the smallholder farming systems. Maize is grown in mixtures most often beans but intercropping with sunflower and cowpeas are also common. Peas are very important crop and are often grown at the beginning of the dry season and are most often grown on broad ridges. Sorghum and millet are also grown, but the production is very minor compared to maize even in the drier areas where, the more drought resistant sorghum would be more appropriate than maize which is much more water demanding. In the area potatoes are an important crop where transport facilities are good they are often grown as a cash crop. The area under cultivation varies considerably within the zone approximately 25–75% with the highest land use pressure in the area around Iringa, where there has been severe overutilization of the land resources which has led to severe erosion.

3. Methodology

The gauging station 1 ka31 (Little Ruaha at Mawande) was used for SWAT2009 model calibration for the period 1971–1979. Daily stream flow data from this station were checked for quality, and this involved the identification of errors from suspicious extreme values. **Figure 3** illustrates the percentage of available data points, missing data points, and removed data points. Six percent (6%) of the data was deleted from the time series, and 2% of the data was missing. Therefore only 92% of the record was used for the calibration method. Both manual and automatic calibration approaches were used for this study. The pre-calibration parameter sensitivity analysis was performed to identify parameters that are expected to have a strong influence on the model simulation results.



	present data	missing data	removed data
■ raw flow	98%	2%	0%
■ filtered flow	92%	2%	6%

Figure 3. Summary of the screened daily stream flow data used in this study.

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In this study, the Sequential uncertainty fitting (SUFI-2) approach was combined with SWAT to quantify parameter uncertainty of the stream flow simulations for the Little Ruaha River (5195 km^2). The SWAT2009 model was setup for the whole GRR basin but the analysis presented here is based on one major tributary only. The hydrological response units (HRU) were characterized using the dominant land use, soil, and slope to keep the complexity of the analysis to a practical limit for the uncertainty propagation. Daily stream flow data from this station were checked for quality, and this involved the identification of errors from unexplained extreme value.

3.1. Sensitivity analysis

Sensitivity analysis allows for the identification of model parameters that exert a strong influence on the model output, thus largely controlling the behavior of the simulation process. In this study, a sensitivity analysis was carried out using the Latin Hypercube One-factor At a Time (LH-OAT) algorithm [8, 14]. The Sensitivity analysis minimizes the number of parameters to be used in the calibration step. The Latin Hypercube simulation is based on a Monte Carlo approach with stratified sampling. The results of the sensitivity analysis are parameters arranged in ranks, where the parameter with a maximum effect obtains rank 1, and parameter with a minimum effect obtains the rank which corresponds to the number of all analyzed parameters. The parameter that has a global rank 1 is categorized as "very important," rank 2–7 as "important," rank 8–27 "slightly important" and rank 28 as "not important" [14].

The sensitivity analysis in this study was done using (i) automatic global sensitivity analysis in SUFI-2, (ii) manual analysis of the sensitive parameters based on the output of the global sensitivity analysis. The global sensitivity analysis in SUFI-2 is not able to analyze all the parameters in SWAT; it analyses the sensitivity of the pre-defined 27 parameters (**Table 1**). In this approach, parameter sensitivity is determined using the multiple regression equations, which regresses the Latin Hypercube generated parameters against objective function values. The *t*-stat and p-value are statistical measures used to evaluate sensitivity in SWAT-CUP. A *t*-stat is used to identify the relative significance of each parameter by providing a measure of sensitivity (larger absolute values are more sensitive). p-Values determined the significance of the sensitivity where a value close to zero has more significance. Both manual and automatic calibration followed the sensitivity analysis. The manual calibration was performed based on the understanding of the sub-basin characteristics. The results of the global sensitivity analysis indicated the sensitive parameters and helped to guide the initial parameter ranges. The calibration procedure involved the following steps:

1. Sensitivity analysis
2. Manual calibration
3. SUFI-2 set up (automatic calibration)
4. Assigning initial parameter ranges
5. Latin Hypercube sampling is used to sample the parameter distributions
6. Model simulations are performed, and objective functions are calculated for each of the n (n = 2000 for this study) simulations.

Parameter	Description	*t*-Stat	*p*-Stat	Rank	Process
ALPHA_BF	Base flow alpha factor for recession constant (days)	−34.23	0.00	1	Ground water
CN2	SCS runoff curve number for moisture condition II	−12.90	0.00	2	Runoff
SURLAG	Surface runoff lag time (days)	−1.54	0.12	3	Runoff
REVAPMN	Threshold water depth in the shallow aquifer for revap (mm)	−1.51	0.13	4	Groundwater
SOL_K(2)	Saturated hydraulic conductivity soil layer 2 (mm h^{-1})	−1.39	0.16	5	Soil
GWQMN	Threshold water depth in the shallow aquifer for flow (mm)	−1.28	0.19	6	Groundwater
SLSUBBSN	Average slope length (mm^{-1})	1.17	0.19	7	Topography
BLAI	Leaf area index for crop	1.05	0.29	8	Crop
CANMX	Maximum canopy storage (mm)	0.60	0.54	9	Runoff
CH_N2	Manning's "n" value for the main channel	0.58	0.55	10	Channel
HRU_SLP	Average slope steepness of the HRU	−0.56	0.57	11	Topography
GW_REVAP	Groundwater "revap" coefficient	−0.46	0.63	12	Groundwater
BIOMIX	Biological mixing efficiency	−0.39	0.69	13	Soil
EPCO	Plant evaporation compensation factor	0.24	0.80	14	Evaporation
SOL_AWC	Available soil water capacity (mm H_2O/mm soil)	0.21	0.82	15	Soil
RCHRG_DP	Deep aquifer percolation fraction	−0.21	0.83	16	Groundwater
ESCO	Soil evaporation compensation factor	−0.10	0.91	17	Evapotranspiration
GW_DELAY	Movement of water from shallow aquifer to the root zone	0.09	0.92	18	Groundwater
CH_K2	Channel effective hydraulic conductivity (mm h^{-1})	0.07	0.94	19	Channel

Table 1. Parameter sensitivity ranking and category of the most sensitive parameters.

3.2. Assigning initial parameter ranges

The results of the sensitivity analysis indicated the sensitive parameters and helped in guiding the setup of the initial parameter ranges. It was important to consider the physical meaning of each parameter and its effects on the sub-basin behavior. Therefore, the initial parameter sets were guided by the understanding of the physical basin characteristics and the default upper and lower limits established in SWAT. In SWAT default parameters can be modified for the whole sub-basin (lumped), or in a distributed way for individual sub-basins or hydrological response units. **Table 2** shows the initial parameter ranges of the sensitive 20 parameters, where the most sensitive parameters are presented in row 2–10.

3.3. Parameter distributions

The identifiability of parameters was examined visually using scatter plots of model parameter values versus CE. **Figure 4** shows scatter plots with the values of each parameter defined versus their corresponding Nash-Sutcliffe efficiency (CE), where the parameter values were obtained from Latin Hypercube sampling of the initial range defined using 2000 simulations. Scatter plots of the parameter values versus objective function were used to examine the identifiability of individual parameters. Based on the scatter plots the identifiable parameters are expected to show a distinct maximum, and lack of a distinct maximum indicates the difficulty in getting the optimal values that give a good model performance, therefore, the parameter becomes poorly identifiable. It is evident that none of the parameters are identifiable.

Parameter	Lower limit	Upper limit	Change option
v__ALPHA_BF.gw	0.00	1.00	Replacement
r__CN2.mgt	−50	50	Relative
v__SURLAG.bsn	0.00	24.00	Replacement
v__REVAPMN.gw	0.11	0.80	Replacement
r__SOL_K (2).sol	0.39	4.28	Relative
a__GWQMN.gw	1983	2889	Absolute
r__SLSUBBSN.hru	0.13	0.33	Relative
v__BLAI{120}.CROP.DAT	3.63	6.95	Replacement
v__CANMX.hru	2.87	8.51	Replacement
v__CH_N2.rte	0	0.3	Replacement
r__HRU_SLP.hru	0	10	Relative
a__GW_REVAP.gw	0.02	0.12	Absolute
r__BIOMIX.mgt	0.11	0.69	Relative
v__EPCO.hru	0	0.4	Replacement
r__SOL_AWC (2).sol	0	0.9	Relative
v__RCHRG_DP.gw	0	1	Replacement
v__ESCO.hru	0	1	Replacement
a__GW_DELAY.gw	0	129	Absolute
v__CH_K2.rte	24.27	94.18	Replacement
r__SOL_K (1).sol	0.66	5.55	Relative

Table 2. Defined upper and lower limits of initial parameter ranges, the extension of the files in which they are located, and the option used for carrying out changes.

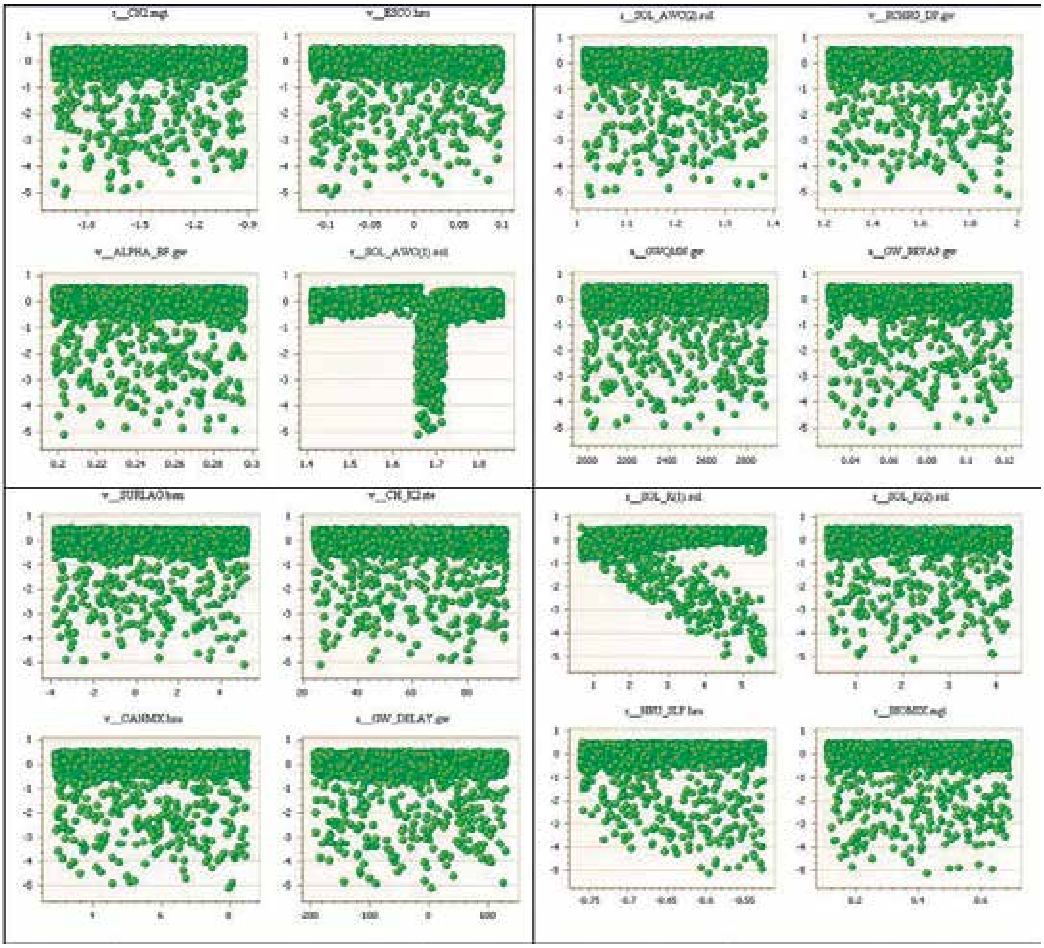

Figure 4. Scatter plots of the calibrated parameters of Little Ruaha River basin (Gauging station 1 ka31) versus Nash-Sutcliffe efficiency, obtained from Latin Hypercube sampling of the large initial range using 2000 simulations.

However, it should be noted that in-identifiability of a parameter does not indicate that the model was not sensitive to these parameters. The sensitivity analysis results identify the most sensitive parameters to be considered for calibration but do not consider the interactions between parameters, therefore having the most sensitive parameters does not mean that the parameter will be identifiable. Estimation of an-identifiable parameters is difficult because there may be many combinations of these parameters that would result in similar model performance (equifinality). Many factors might have led to the non-identifiability of parameters in this study. The interactions between parameters may have contributed to the equifinality which might be associated with the simplified representation of the sub-basin (dominant HRU). Interactions between soil parameters (soil depth and available water capacity) and ground water parameters (Groundwater delay) is expected in SWAT. It is hard to explain these interactions since SWAT considers two soil layers (root zone and unsaturated zone) and ground water (conceptual shallow and deep aquifer stores) and there is not enough information regarding sub-surface water processes to will enable a better explanation of the parameter interactions.

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3.4. Final calibrated parameter ranges

Latin Hypercube sampling was used to sample parameters within the initial ranges using 2000 ensembles and a uniform distribution. The CE was used to get optimum parameter values and to separate behavioral from non-behavioral parameter sets, where a cutoff limit of CE = 0.45 was used. **Table 3** shows the parameter range and optimal value for the best simulation. ALFA_BF is the most sensitive parameter followed by CN. **ALPHA_BF** parameter is a direct index of ground water flow response to changes in recharge. The ALPHA_BF value between 0.1 and 0.3 reflects an area with the slow response to changes in flow, a value of 0.9–1 reflects an area with a rapid response to changes in flow. For the Little Ruaha sub-basin, a value of 0.25 was obtained. The CN is the parameter that determines the amount of runoff to be generated from a sub-basin, so it was expected to be sensitive for the Little Ruaha sub-basin with an optimal value of −1.69. **SURLAG** was the third most sensitive parameter and is the fraction of runoff that reaches a sub-basin outlet on any given day. SURLAG was sensitive for this sub-basin because of the low time of concentration, and an optimum value of 3.5 days was obtained. **REVAPMN** presents the threshold depth of water in the shallow aquifer for return flow to the root zone to occur. This parameter is most important in areas where the water table is high or areas with deep-rooted crops. An optimum

Parameter name	Lower limit	Upper limit	Optimal SUFI-2
v__ALPHA_BF.gw	0.00	1.00	0.25
r__CN2.mgt	−50	50	−1.69
v__SURLAG.bsn	0.00	24.00	3.5
v__REVAPMN.gw	0.11	0.80	0.57
r__SOL_K (2).sol	0.39	4.28	1.36
a__GWQMN.gw	1983	2887.18	2071.38
r__SLSUBBSN.hru	0.13	0.33	0.32
v__BLAI{120}.CROP.DAT	3.63	6.95	4.82
v__CANMX.hru	2.87	8.51	5.95
v__CH_N2.rte	0	0.3	0.06
r__HRU_SLP.hru	0	10	0.75
a__GW_REVAP.gw	0.02	0.12	0.10
r__BIOMIX.mgt	0.11	0.69	0.40
v__EPCO.hru	0	0.4	0.004
r__SOL_AWC (2).sol	0	0.9	1.10
v__RCHRG_DP.gw	0	1	1.94
v__ESCO.hru	0	1	0.02
a__GW_DELAY.gw	0	129	−31.05
v__CH_K2.rte	24.27	94.18	59.94
r__SOL_K (1).sol	0.66	5.55	0.66

Table 3. Final parameter ranges calibrated using SUFI-2.

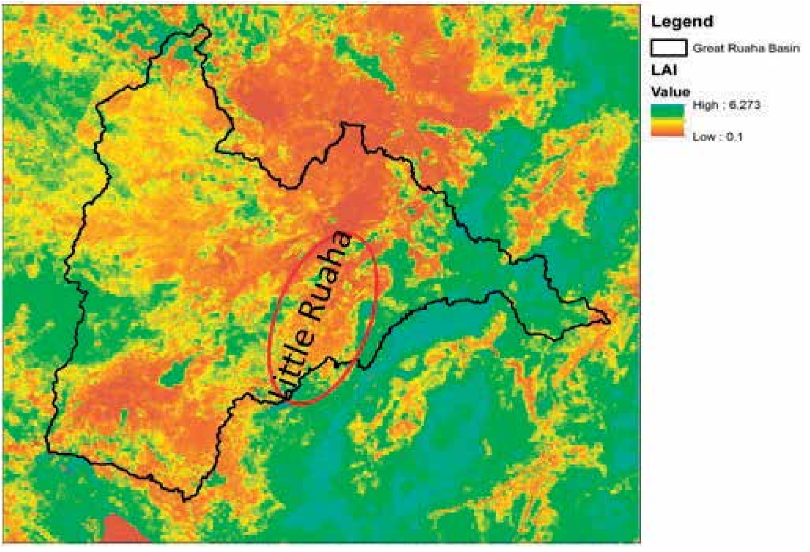


Figure 5. Spatial variations in leaf area index within the Little Ruaha basin.

value of 0.57 was obtained. SOL_K (2) is the saturated soil hydraulic conductivity (mm h^{-1}). In this study, a SOL_K value of 1.66 mm h^{-1} was used. This parameter relates to water flow rate to the hydraulic gradient and is a measure of the rate of water movement through the soil.

The **GWQMN** is the threshold water level in the shallow aquifer for return flow to occur (mm). The ground water flow to the main channel is allowed only when the depth of water in the shallow aquifer is equal to or greater than the threshold depth of water in the shallow aquifer required for the return flow to occur. An optimum value of 2071.38 (mm) was obtained. The obtained value for the mean slope steepness of the basin (**SLSUBBSN**) is 0.32, indicating that the sub-basin is influenced by low to moderate slopes and has implications for the runoff generation process. The optimum value for the maximum potential **LAI** is 4.82. The value corresponds to the MODIS data which indicates LAI for the Little Ruaha catchment ranges from low to moderate values (**Figure 5**). **CANMIX** represents the maximum canopy area, and an optimum value of 5.95 mm was obtained. This value corresponds to the leaf area index indicated in (**Figure 5**). The Manning roughness coefficient "n" for channel flow (**CH_N (2)**) is the parameter that influences channel roughness, an optimum value of 0.06 was obtained.

4. Model simulation results and uncertainty analysis

SWAT was calibrated against observed data for gauging station 1 ka31 for the period 1970–1971. Calibration results yielded satisfactory results given the data scarcity. CE and R^2 values of 0.54 and 0.62 were achieved for the calibrated period. The P-factor (% of measured data bracketed by 95% prediction uncertainty) was 0.58 and 0.21 for the full range and behavioral simulations, respectively. The R factors for the full range and behavioral parameters were

1.91 and 0.36, respectively. These results confirm quite large uncertainty of the simulated discharge due to the large equifinality in parameters and reliability of input data (precipitation and daily evaporation data). **Table 4** shows a summary of model performance for the calibrations and a comparison between all parameter sets (full range) and behavioral parameter sets. In presenting results, the following performance measures were used;

- The relative distance between the observed data and the 95PPU (R-factor)
- The percentage of observations covered by the 95PPU (P-factor)
- Nash-Sutcliffe efficiency (CE)
- Coefficient of correlation (R^2)

Station	Simulations	P-factor	R-factor	CE	R2
1ka31	Full range	0.58	1.91	54%	62%
	Behavioral	0.21	0.36	54%	62%

Table 4. Summary of performance statistics for the best simulation.

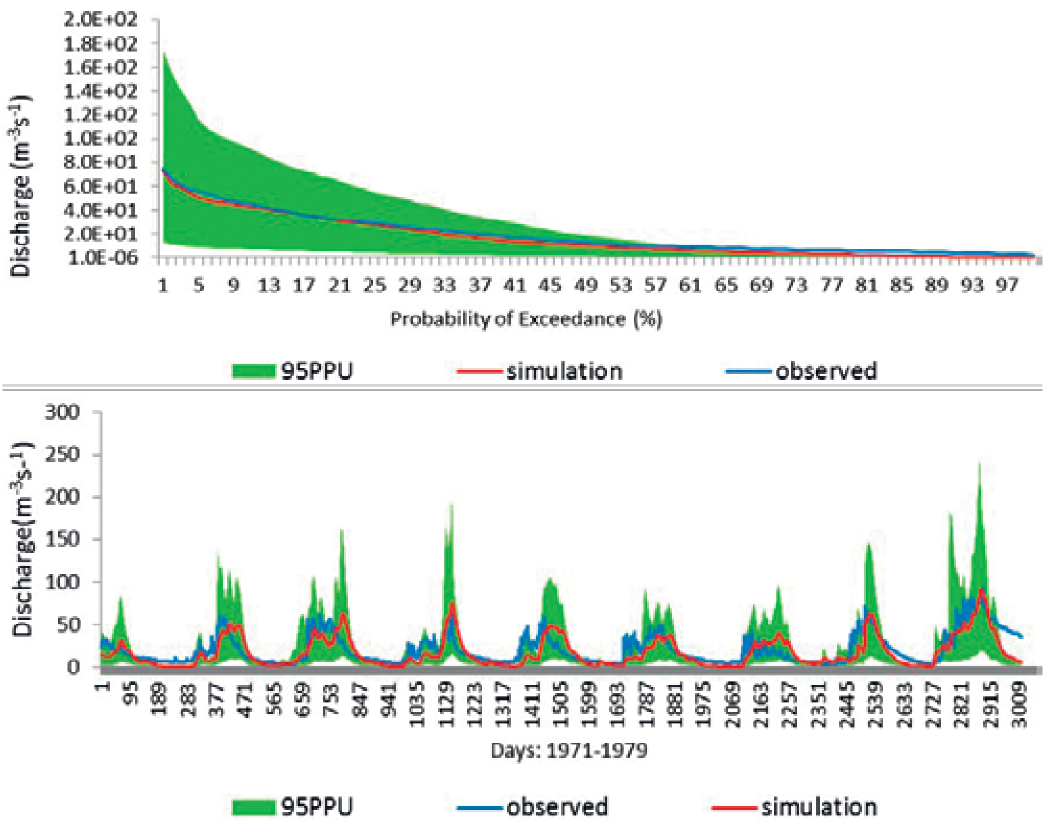
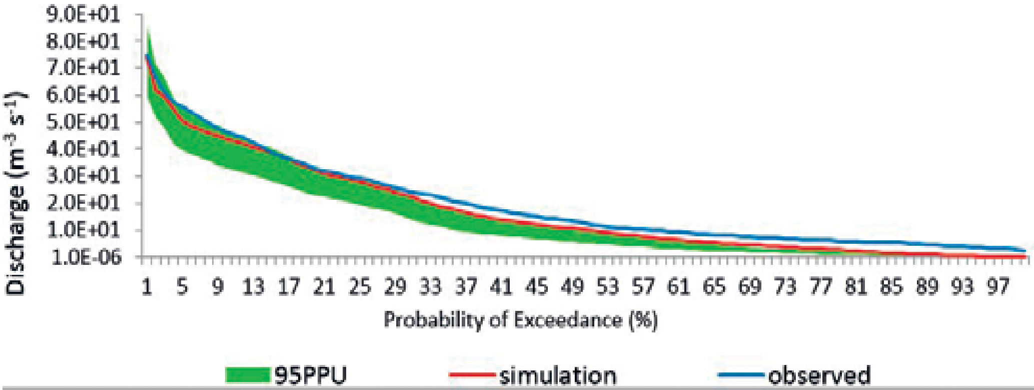


Figure 6. Calibration at 1 ka31-Mawande (95PPU for full range simulations).

Uncertainty analysis was implemented using the SUFI-2 algorithm. **Figures 6** and **7** show the results of the daily flow uncertainty analysis carried out in the sub-basin for the full range and behavioral parameter sets respectively. The shaded area represents the 95% predictive uncertainty (95PPU), whereas the blue lines correspond to the observed discharges and the red lines correspond to the simulated flow at the sub-basin outlet. For the full range simulations (**Figure 6**) it was found that the observations fall within the lower and upper 95% prediction uncertainty in high and moderate flow but with large uncertainty. **Figure 6** shows that the 95% prediction uncertainty of behavioral simulations (CE ≥ 45%) does not bracket the observed flow, only 15% of the data were bracketed, indicating that some processes are not well represented in the model. The prediction limits obtained with SUFI-2 are highly dependent on the threshold selected to separate behavioral from non-behavioral parameter sets. It is also important to note that in SUFI-2 parameter uncertainty is presented as a uniform distribution in the final parameter range, while parameter interactions are ignored and contribute to the large equifinality observed in these results.

Final calibration parameters for the Little Ruaha Drainage System with a Coefficient of Evaluation (CE) of 0.54 and R^2 of 0.62 for the best simulation regardless of the parameter set. The results



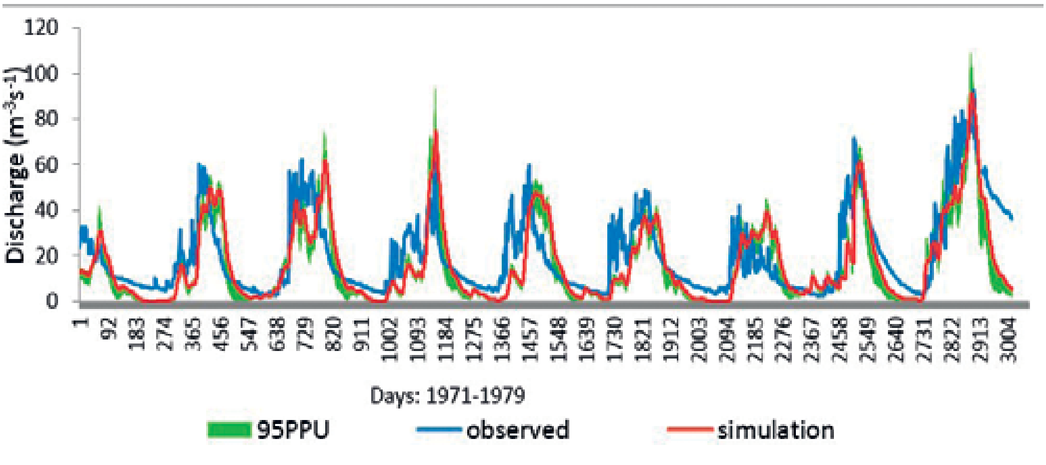


Figure 7. Calibration at 1 ka31-Mawande (95PPU for behavioral simulations).

show reasonable performance in the hydrologic simulations but with large uncertainties. The model performance statistics achieved in this study are like the ones achieved in other studies in Tanzania [10], but one point that should be noted is that, after calibration, parameters should have physical meaning. With the large equifinality in the parameter sets, it was not possible to get identifiable parameter sets, and it is hard to say that behavioral parameters sets are representatives of the basin's behavior. This observation highlights the challenges associated with implementing SWAT for water resources use in Tanzania and other developing countries.

5. Discussions and conclusions

The SWAT2009 was applied to the Little Ruaha sub-basin. The model was set up using a coarse spatial dataset, interpolated rainfall data, and a single dominant HRU. Sensitivity analysis results showed that ALPHA_BF, CN2, SURLAG, REVAPMN, CH_K2, GWQMN, SLSUBBSN, BLAI, and CANMX are the most sensitive parameters in the basin. The Little Ruaha drainage system falls within the African land surface where the infiltration of the topsoil is good, and interflow is an important part of the total River discharge. The soils in the upper part are deeply weathered and have a good soil structure. This explains the sensitivity of the surface and subsurface parameters. The drainage is dominated by steep topography, and this explains the sensitivity of the mean slope length of the basin. Sensitivity analyses enabled the most sensitive model parameters to be identified for further calibration, but this does not mean that sensitive parameters will also be identifiable. Out of the 27 parameters, 20 were identified as sensitive, but the interactions between these parameters were not considered during the sensitivity analysis.

Final calibration parameters for the Little Ruaha Drainage System are presented in **Table 4**, with a CE of 0.54 and R^2 of 0.62 for the best simulation regardless of the parameter set. This is since the behavioral parameter sets are within the non-behavioral parameter sets. The results show reasonable performance in the hydrologic simulations but with large uncertainties. The model performance statistics achieved in this study are like the ones achieved in other studies in Tanzania [10], but one point that should be noted is that, after calibration, parameters should have physical meaning. With the large equifinality in the parameter sets, it was not possible to get identifiable parameter sets, and it is hard to say that behavioral parameters sets are representatives of the basin's behavior. Ref. [13] reviewed the use of the SWAT model in the Nile Basin countries, including Tanzania, and found that the model produced satisfactory or good results, but almost all the case studies reviewed gave results based on the wrong process representation. These results were problematic because when different studies in the same or similar sub-basins are compared, they give different results. In peer-reviewed papers [9, 10] some documented parameter values were not realistic, but this information was not reported in those papers [11]. This observation highlights the challenges associated with implementing SWAT for water resources use in Tanzania and other developing countries.

Even though the model gave satisfactory results based on the performance measures, a critical analysis of **Figures 6** and **7** suggests a different picture. **Figure 6** showed that there is good agreement between observed and simulated flow but associated with very large uncertainty in high to moderate flows, and the uncertainty band does not bracket the low flows. Running the model with the behavioral parameter sets shows a reduction in P-factor and R-factor values (**Table 4**). **Figure 7** shows that while the uncertainty band has been reduced, the model is under-simulating both high and low flows, and does not bracket the moderate to low flows. This could be associated with input data uncertainties, or some processes are not well represented in the model. ALPHA_BF was the most sensitive parameter identified through the sensitivity analysis, and apart from a lack of observed ground water information, difficulties of SWAT in simulating ground water flow [12] might have contributed to the negative aspects of these results.

This study assessed model uncertainty using a combined uncertainty approach that assumes all sources of uncertainty have been considered within the model. In such an approach it is hard to separate the sources of uncertainty, and therefore a follow-up analysis of uncertainty should be undertaken by determining how erroneous input data influence model results. Although not assessed within the research questions of this study, the results highlight potential uncertainties in the input rainfall and evaporation data. The use of these data was justified and used in the simulations but could potentially have influenced the overall model performance and uncertainties that cannot be explained.

The uncertainty analysis was carried out using 20 sensitive parameters, which is a large number considering the interactions between them. Therefore, some less sensitive parameters should be fixed and allow only the most sensitive parameters to vary. This will reduce the effect of parameter interactions and hence the none-uniqueness problem. Although this model has been shown to generate reasonable results, it is worthwhile to consider the challenges associated with setting up a distributed model. In this research, large-scale spatial datasets have been used, and a homogenous model was assumed because the spatial data resolution was insufficient to represent large numbers of hydrological response units. However, even when the resolution was sufficient, attribute values for most of the parameters are lacking. Because of difficulties associated with parameter representation across spatial scales, it is better to use a homogenous set up because biases and uncertainty can be added by the modeler when trying to parameterize values within the hydrological response unit at a size larger than its coverage. The overall conclusions from this assessment include;

- The SUFI-2 approach has capabilities of identifying behavioral parameter. However, the results are influenced by large equifinality.
- The scatter plots of the parameter values against objective functions obtained after simulation provided an initial qualitative overview of the uncertainties involved in the representation of basin's behavior.
- The 95% of the predictive uncertainty (95 PPU) for stream flow computed using SUFI-2 using the Latin Hypercube sampling with 2000 runs, did not bracket all simulations, indicating that some processes are not represented in the model. Hence additional information is needed to improve the results.
- It is also important to emphasize that the prediction limits obtained with SUFI-2 are highly dependent on the threshold selected to separate behavioral from non-behavioral parameter sets and that the subjective choice of the threshold value and objective function can lead to additional uncertainty in the simulation results.

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Developing an understanding of the hydrological processes that occur in a system is critical for the effective assessment and management of water resources. However, the lack of observational data represents a serious challenge to understanding that is difficult to resolve, especially when there are so many factors that contribute to hydrological variation and change. Scientists and practitioners within the southern African region are attempting to develop the most effective methods for water resources assessment that will contribute to effective water resources management. This study has employed the uncertainty approach for setting up the rainfall-runoff model for the Little Ruaha River basin and the assessment of uncertainties associated with simulations of naturally hydrological responses. The aim was to explore uncertainties in modeling hydrological responses and to establish a behavioral model that can be used for water resources management and future decision making. This approach has addressed a range of key issues in hydrological modeling; these include the uncertainties associated with input data, parameter equifinality and the importance of realistic uncertainty representation using constraints.

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Section 2

Flood and Drought Management

Chapter 5

Historical, Hydrological and Hydraulics Studies for Sustainable Flood Management

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Additional information is available at the end of the chapter

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Abstract

Extreme events such as floods can endanger human lives and cause large economic damage. The Savinja River catchment is one of the most frequently flooded areas in Slovenia, Europe. In order to evaluate the impact of the proposed flood mitigation measures on the flood safety in this catchment, the combined hydrological and hydraulic modelling approach was carried out. The hydrological model Hydrologiska Byråns Vattenbalansavdelning (HBV-light) was used to perform hydrological modelling. The hydraulic calculations were carried out using the HEC-RAS 5.0.3 model in order to simulate the combined one- and two-dimensional unsteady flow. Using the calibrated and validated hydrological and hydraulic models, the impact of the proposed measures was assessed in the light of the sustainable flood management. Additionally, with analyses of the historical data and past flood events, we were able to investigate the characteristics of the extreme floods in this area and also downstream at the confluence with the Sava River. Moreover, it was found that the backwater effect has an important role on the water level and flood safety along the river reach, which is often neglected in the aspect of flood management.

Keywords: flood management, hydrological modelling, hydraulic modelling, Savinja catchment, historical events

1. Introduction

Water regime and questions related to floods are usually consequences of the development in the past. Today's look of the rivers and streams in some parts of the Europe is still a result of the construction works from Roman times (**Figure 1**). Construction works began to intensify two centuries ago when large inundation areas were taken away from rivers for agricultural purposes. Due to the reduction of inundation areas, the river flows increased, and narrow river channels could not carry it anymore. Nowadays, we can see the consequences of the development in the past, and we are looking for sustainable solutions for the next centuries and next generations. Fortunately, we have a lot of observations, measurements, experiences and sophisticated tools [1] to support decision-making processes in order to achieve the sustainable flood management. This study focuses on the flood safety in the Slovenia that is part of the Danube River basin [2].

The inundated areas endangered due to the extreme floods (floods with 100-year return period: Q100) in Slovenia cover about 700 km^2, which is about 4% of the total area of the country and urban areas such as Celje and Ljubljana cities [3]. The Savinja River catchment is one of the areas with the highest flood risk potential in Slovenia, especially highly populated and urbanised areas, as, for example, cities Celje and Laško were often severely damaged during the floods in the past [3]. City Celje can be even regarded as the town with the highest flood risk in Slovenia with the first flood benchmark dating back to 1672 [3]. Large floods occurred in this area in 1954 (**Figure 2**), 1989, 1990, 1998 and 2007 [3, 4]. Due to the potential further climate changes (e.g. climate change or variability) or land-use changes, the flood risk could increase in the future [5–7]. Therefore, the effective flood protection measures have to be taken in order to reduce the potential flood damage also considering the hydrological variability and at the same time, not to worsen the situation downstream at the confluence with the Sava River and consequently, at the location of the Krško Nuclear Power Plant and several hydropower plants that are located in this area (lower Sava River in Slovenia). With this regard, the characteristics of the past extreme events have to be taken into account when planning floods' protection measures or implementing sustainable flood management.

Therefore, the main aim of this study was to investigate the flood safety in the Savinja River catchment and to analyse the influence of the proposed flood protection measures on flood

Figure 1. Austrian military map of the Celje city (on map Zilli) from the period 1763 to 1787 [8, 9].

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Figure 2. Floods in Celje city in 1954 [10].

safety in this catchment. The combined hydrological-hydraulic analyses were performed in order to achieve this aim. Moreover, influence of the backwater effect on the flood safety was also investigated.

2. Data and methods

Savinja River catchment is part of the Sava River catchment that drains into the Danube River. The Savinja River catchment covers about 1851 km^2 (**Figure 3**). Due to its topography, the Savinja River catchment has significant torrential characteristics [11].

In the processes of the model development and hydrological analysis, officially measured data were used (Slovenian Environment Agency). Discharge data from stations located on the following rivers in the Savinja catchment was applied: Lučnica, Dreta, Bolska, Rečica, Paka, Ložnica, Hudinja, Voglajna and Savinja. These are the main tributaries of the Savinja catchment that have relatively significant influence on the flood safety in the Savinja catchment (**Figure 4**). Peak discharge information (different data periods ranging from 1907 to 2013) was used to perform the flood frequency analysis, and hourly data were applied in the process of hydrological and hydraulic models' development. Moreover, precipitation, potential evapotranspiration and air temperature data from several stations in the area were also included in the hydrological model.

2.1. Hydrological model

The Hydrologiska Byråns Vattenbalansavdelning (HBV-light) model [12] and PEST model calibration software [13] were used in the process of model development. This hydrological

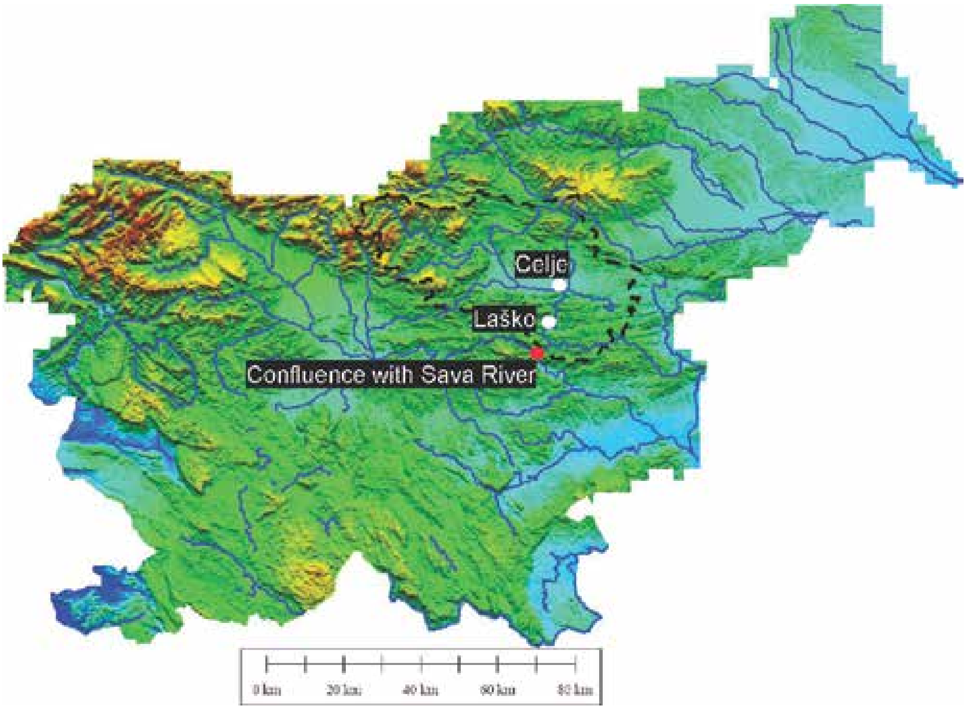

Figure 3. The Savinja River catchment on a map of Slovenia with indicated cities Celje and Laško and confluence of the Savinja River and Sava River. Important infrastructure such Krško Nuclear Power Plant is located downstream of the confluence of the Savinja and Sava Rivers.

model was already used for the flash flood forecasting in the Savinja River catchment [11] and was also recently used for the hydrological analysis and modelling of the large flood in the Bosna River catchment that occurred in May 2014 [14]. As an alternative in some other hydrological applications, some other hydrological model with different characteristics such as HEC-HMS or SWAT model [2, 15] could be used.

Figure 5 shows the model scheme of the Savinja catchment as it was defined in the HBV-light model. The Savinja catchment was initially divided into 21 sub-catchments (each of these sub-catchments was described with 34 parameters) that were selected based on the discharge data availability, and these 21 sub-catchments were eventually further divided into 77 sub-catchments (**Figure 6**). Thiessen polygons were applied to determine the spatial rainfall distribution (**Figure 7**). Moreover, in the process of model calibration and validation, daily rainfall data were also used in order to increase the density of rainfall stations in the Savinja catchment (hourly rainfall distribution from the nearest station was combined with daily rainfall amounts). Mean monthly evapotranspiration values for stations Celje, Maribor, Starše and Šmartno pri Slovenj Gradcu were also used as part of the hydrological modelling.

Calibration of the hydrological model HBV-light was carried out using the PEST software [13] that was already used for this purpose in case of the Bosna River catchment [15]. Due to the large number of parameters (34 for each sub-catchment) and consequently, high computational

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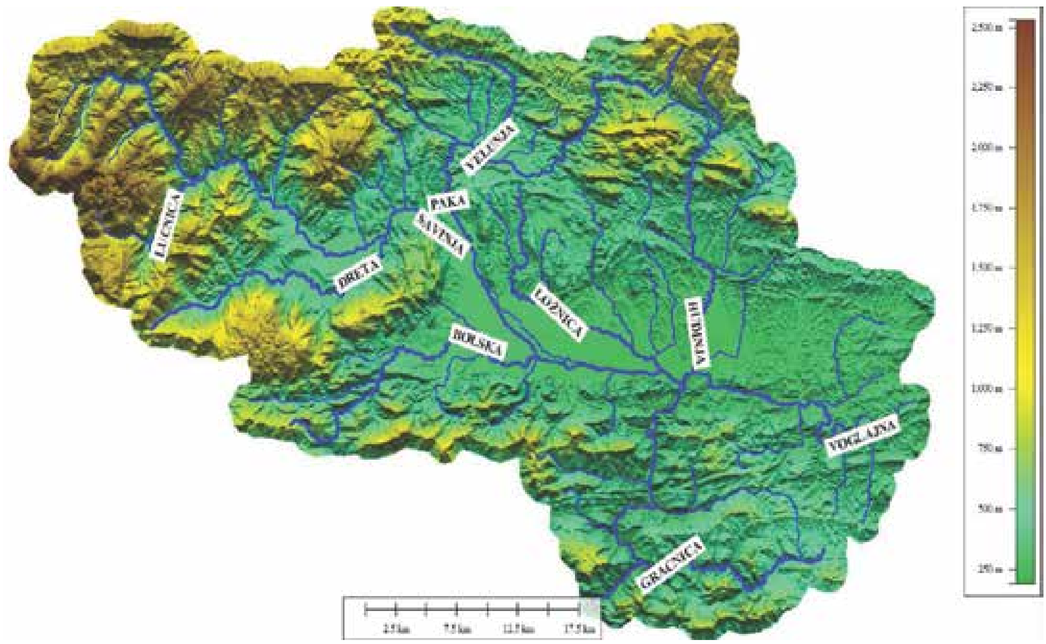

Figure 4. The Savinja River catchment with the most important rivers from the flood safety perspective. Note that Celje city is located at the confluence of the Savinja, Hudinja and Voglajna Rivers and that about 90% of the total Savinja catchment drains into this confluence; only 10% of the area contributes to runoff downstream of this location.

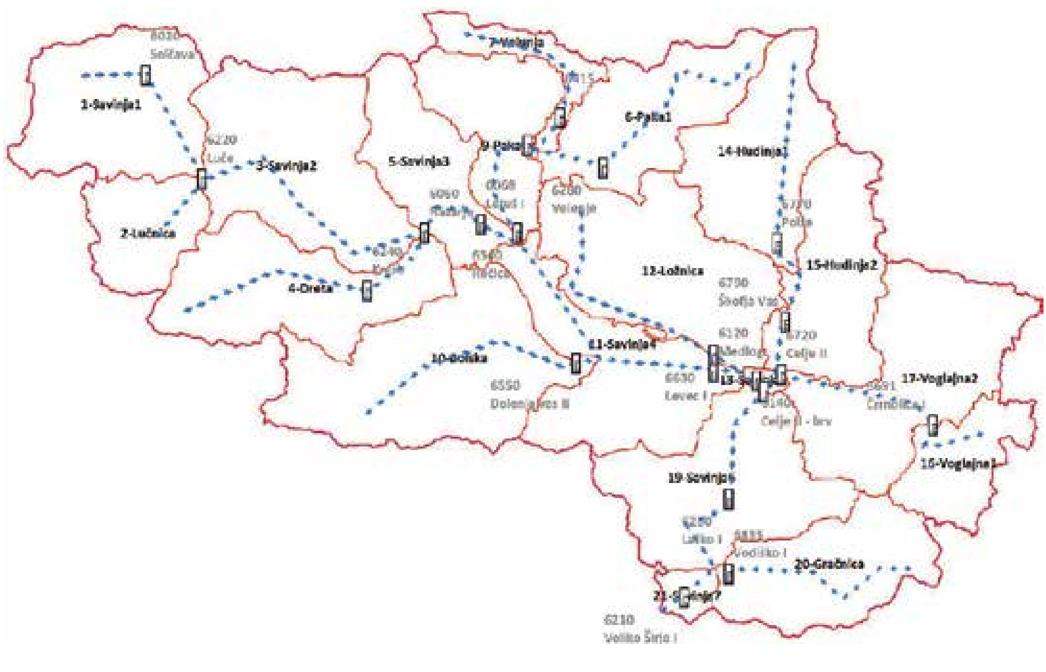

Figure 5. Modelling scheme of the Savinja River catchment with discharge gauging stations that were applied in this study.

Figure 6. Hydrological model scheme of the Savinja River catchment with 77 sub-catchments.

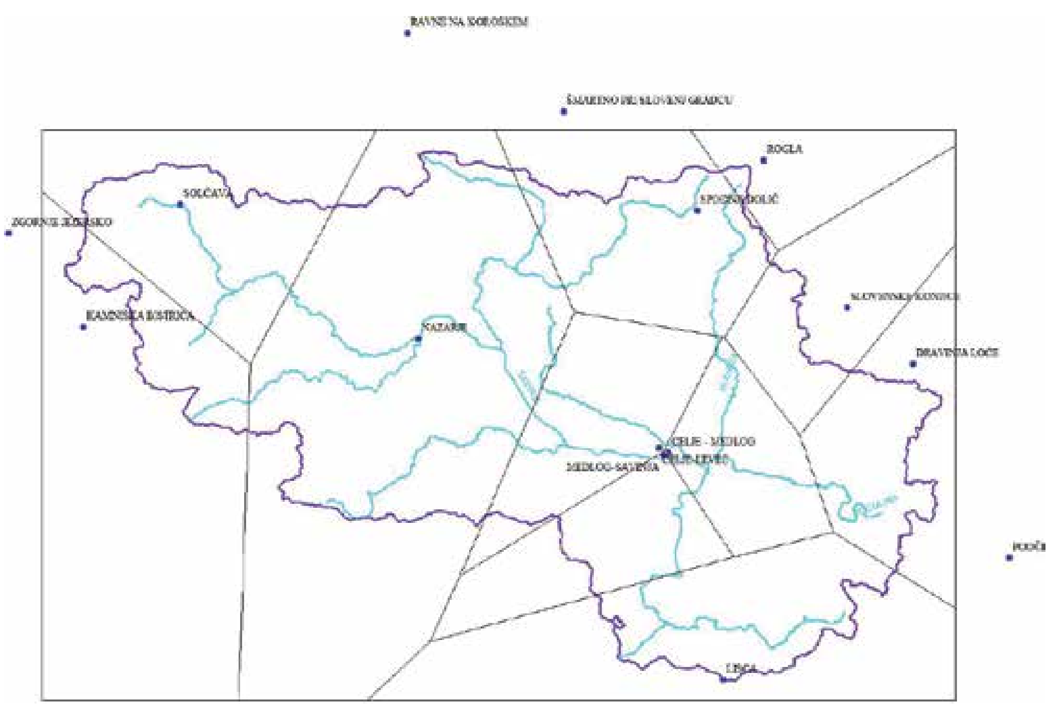

Figure 7. Thiessen polygons for rainfall stations with hourly rainfall data availability that were used in the process of the hydrological model development.

demands, the beoPEST module was used for parallel calibration of the hydrological model. Hourly discharge data and information about peak discharge values were used in the process of model calibration, whereas the initial parameter values and limits were defined based on the experiences obtained from the Bosna River modelling [15].

2.2. Hydraulic model

The Savinja River catchment was also modelled with the hydraulic model HEC-RAS 5.0.3 that enables one- or two-dimensional unsteady flow simulations [16]. One-dimensional calculations were performed in the river channel, and two-dimensional calculations were conducted on the floodplain areas. Detailed model description is available in the HEC-RAS user's manual [16]. The most important rivers in the Savinja catchment from the flood safety perspective were included in the model (Dreta, Ložnica, Voglajna, Hudinja and Savinja Rivers); other rivers were considered in the model as lateral inflows into the Savinja River. Average slope of these modelled rivers varies from 0.2 to 0.6%. In total, more than 135 km of river network with more than 2400 cross sections were incorporated in the model. Geodetically measured river cross sections were combined with 1 m digital terrain model of the Savinja catchment. The selected Manning roughness coefficients were between 0.03 and 0.04 for the river channel, between 0.035 and 0.05 for the flood area within the cross section and between 0.06 and 0.1 for the 2D flood area. The size of cells covering 2D flood areas was between 20 × 20 m and 30 × 30 m (computational mesh). However, it should be noted that each cell is described with hydraulic

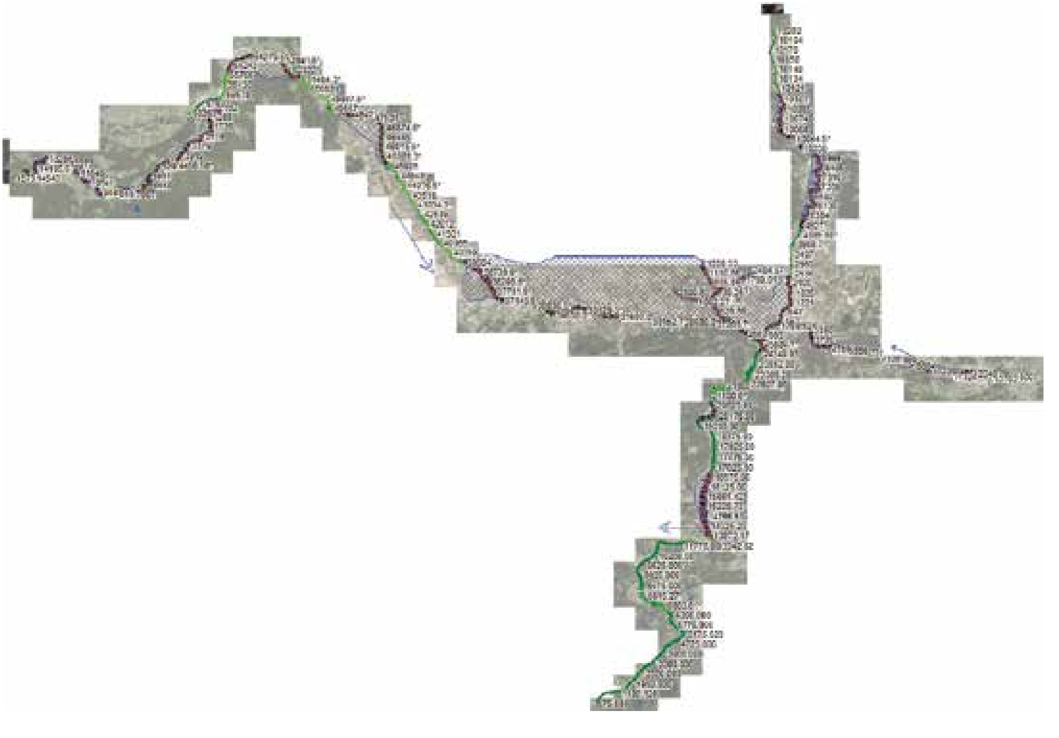

Figure 8. The extent of the hydraulic model from the confluence of Dreta and Savinja Rivers to the confluence of Savinja and Sava Rivers (including Dreta, Ložnica, Voglajna, Hudinja Rivers).

properties table based on the underlying digital terrain model used (1 m resolution). The HEC-RAS pre-processor computes the elevation-volume relationship and other geometric characteristics crucial for hydraulic calculations for each cell face [16]. **Figure 8** shows the main rivers that were included in the hydraulic model from the confluence of the Savinja and Dreta Rivers to the confluence of the Savinja and Sava Rivers. It should be noted that due to the improved 2D modelling algorithm that is implemented in the HEC-RAS version 5 [16], the entire 135 km of the river network with multiple flood areas was modelled as one model. Moreover, the total computational time did not exceed 2.5 h.

3. Results and discussion

This section presents the results of hydrological and hydraulic model calibration and validation and some results of the investigation of the influence of the proposed flood safety protection measures in the Savinja River catchment.

3.1. Hydrological model and analysis

The hydrological model was calibrated based on the flood event that occurred in September 2007 and caused large damage in different parts of Slovenia [2]. The average value of the Nash-Sutcliffe coefficients for the calibration of the model for the 21 sub-catchments (with available discharge data) was 0.85. **Figure 9** shows an example of the calibration results for the location of the Laško gauging station on the Savinja River with the Nash-Sutcliffe coefficient as 0.93.

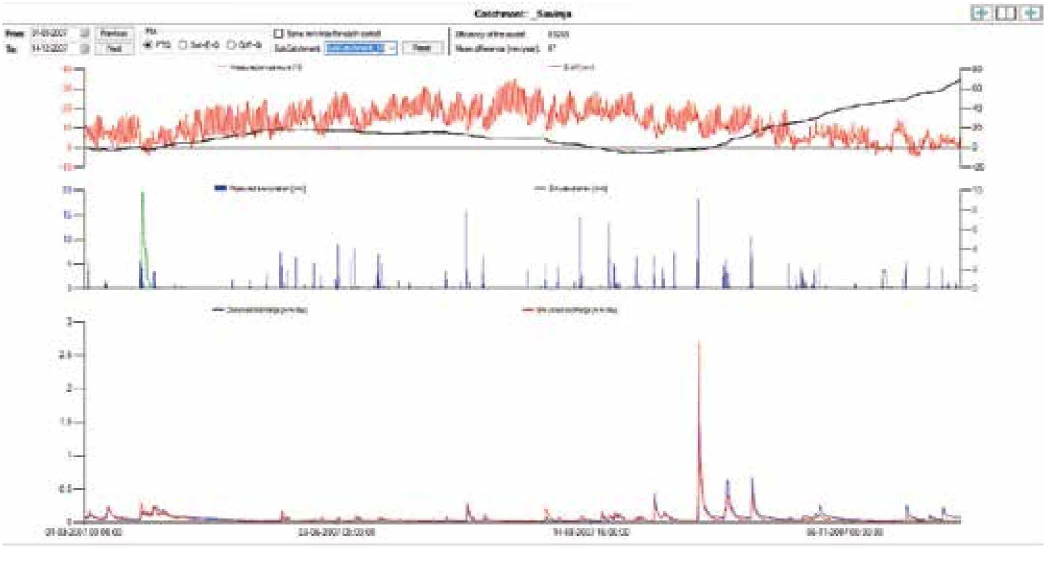

Figure 9. Hydrological model calibration results using the data from year 2007 for the station Laško on the Savinja River (in the lower figure with red and blue is simulated and observed discharge, respectively).

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The validation of the model was performed using the data from floods that occurred in years 1990 and 1998 and also caused large damage in the Savinja River catchment [3, 4]. For the 1990 event, the average value of the Nash-Sutcliffe coefficients for nine stations with available data was 0.85. Using the calibrated and validated hydrological model, we were able to reconstruct the hydrological situation in the Savinja catchment also for the locations where discharge data were not available (either no gauging station or station was damaged during the flood) for floods that occurred in years 1990, 1998 and 2007. **Table 1** shows calibration results for the 2007 flood event for 19 sub-catchments where measured discharge data were available in order to perform evaluation of the hydrological model. Moreover, **Table 2** shows hydrological model validation results for the 1990 flood event for gauging stations with available measured discharge data. The number of gauging stations in the 1990 was smaller than in the case of 2007 because gauging network was extended in the recent decades and several gauging stations were damaged during the 1990 flood event.

Sub-catchment	Model discharge sum [mm/period]	Measured discharge sum [mm/period]	Nash-Sutcliffe	R^2
1-Savinja1-Luče	566	573	0.91	0.91
2-Lučnica-Luče	818	895	0.93	0.93
3-Savinja2-Nazarje	750	801	0.84	0.85
4-Dreta-Kraše	741	764	0.98	0.98
5-Savinja3-Letuš	727	718	0.98	0.98
6-Paka1-Velenje	475	451	0.80	0.80
7-Velunja-Gaberke	454	455	0.73	0.73
8-Paka2-Šoštanj	419	350	0.78	0.86
9-Paka3-Rečica	400	428	0.85	0.85
10-Bolska-Dolenja_vas	489	521	0.90	0.91
11-Savinja4-Medlog	551	506	0.94	0.95
12-Ložnica-Levec	332	394	0.91	0.91
13-Savinja5-Celje_brv	525	509	0.94	0.95
14-Hudinja1-Polže	347	379	0.89	0.89
15-Hudinja2-Škofja_vas	298	344	0.94	0.95
17-Voglajna2-Celje	201	288	0.26	0.45
19-Savinja6-Laško	445	459	0.92	0.93
20-Gračnica-Vodiško	296	337	0.68	0.70
21-Savinja7-Veliko Širje	425	448	0.67	0.78

Note that computational period to calculate discharge sum was from 1.3.2007 to 14.12.2007.

Table 1. Hydrological model calibration results for the 2007 flood event for the 19 sub-catchments where measured discharge data were available.

Sub-catchment	Model discharge sum [mm/period]	Measured discharge sum [mm/period]	Nash-Sutcliffe	R^2
1-Savinja1-Luče	2562	3010	0.85	0.89
4-Dreta-Kraše	4442	4901	0.90	0.92
5-Savinja3-Letuš	4285	3692	0.59	0.89
12-Ložnica-Levec	1453	1845	0.94	0.96
13-Savinja5-Celje_brv	2970	3111	0.97	0.98
15-Hudinja2-Škofja_vas	1278	1382	0.79	0.83
17-Voglajna2-Celje	1011	1478	0.79	0.87
19-Savinja6-Laško	2444	2582	0.97	0.97
21-Savinja7-Veliko Širje	2320	1301	0.84	0.91

Table 2. Hydrological model validation results for the 1990 flood event for the sub-catchments where measured discharge data were available.

In order to define the design hydrographs, the flood frequency analysis was also performed. The annual maximum method was used for sample definition and log-Pearson type III distribution was applied to define the relationship between design discharge and return period.

3.2. Hydraulic model and analysis

The calibration and validation of the hydraulic model were also performed using the data from 1990, 1998 and 2007 floods. Besides discharge data, information about water level was also used (rating curves were used to transform water level data to discharge). Comparison between the measured maximum flood extent on the floodplain areas and computed inundation extent was also carried out. **Figure 10** shows an example of the calibration results for the gauging station Celje on the Savinja River in the year 1990. Similar results were also obtained for some other gauging stations in the Savinja catchment for the 1990, 1998 and 2007 events. Model evaluation was performed on rivers Dreta, Ložnica, Voglajna, Hudinja and Savinja. **Figure 11** shows calibration results for the large natural floodplain area before the Celje city for the 1990 event. Similar graphical comparison was also carried out for other flooding areas.

3.3. Flood safety

The calibrated and validated hydrological and hydraulic models of the Savinja River catchment were used to investigate the impact of the proposed flood protection measures on the flood safety. The main suggested flood protection measures are dry retention (flood-control) reservoirs that are planned to be built at several locations in the Savinja catchment. Eight flood-control reservoirs are to be constructed in the location of the large natural flood area before the Celje city (**Figure 11**). Relatively sophisticated and complex hydro-technical equipment is selected to operate these reservoirs with the total volume of approximately 8×10^6 m^3. **Figure 12** shows comparison between three different situations, namely natural-actual conditions during the 1990 event, full operation of the proposed flood-control reservoirs with increased volume

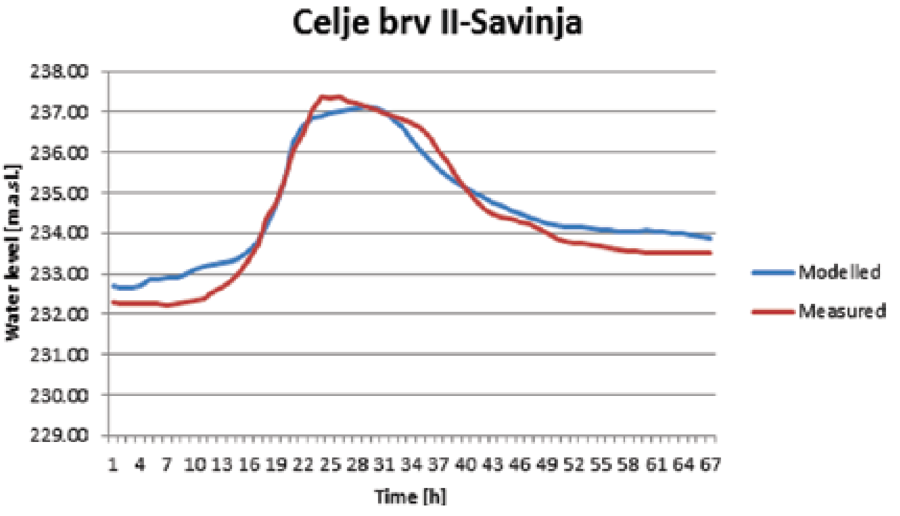

Figure 10. Calibration results for the gauging station Celje on the Savinja River for the 1990 event (blue is modelled water level and red is measured water level by the Slovenian Environment Agency).

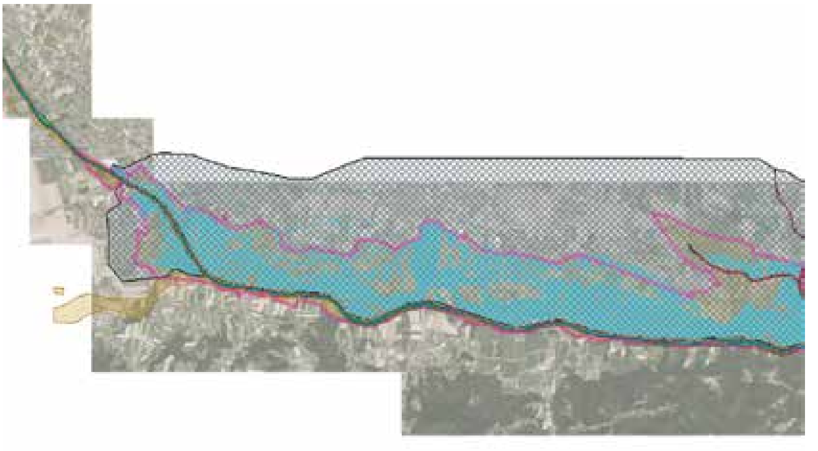

Figure 11. Calibration results for the largest natural floodplain area before the Celje city for the 1990 event (light blue is modelled extent of floodplain inundation by combined 1D/2D model and grey with pink outline is measured extent of floodplain inundation).

(retention of 10×10^6 m^3) and proposed flood-control reservoirs that failed to operate. We can conclude that proposed flood-control reservoirs reduce the peak discharge for about 150 m^3/s; however, potential technical problems with hydro-technical equipment would lead to an increase in peak discharge for approximately 100 m^3/s due to the exclusion of large natural floodplain area (**Figure 12**). It can be seen that the construction of the reservoirs would lead to about 15% decrease in the peak discharge compared to the natural conditions during the 1990 event. This means that the flood risk downstream of the Celje city would decrease in case of operation of reservoirs without any problems and according to the procedure.

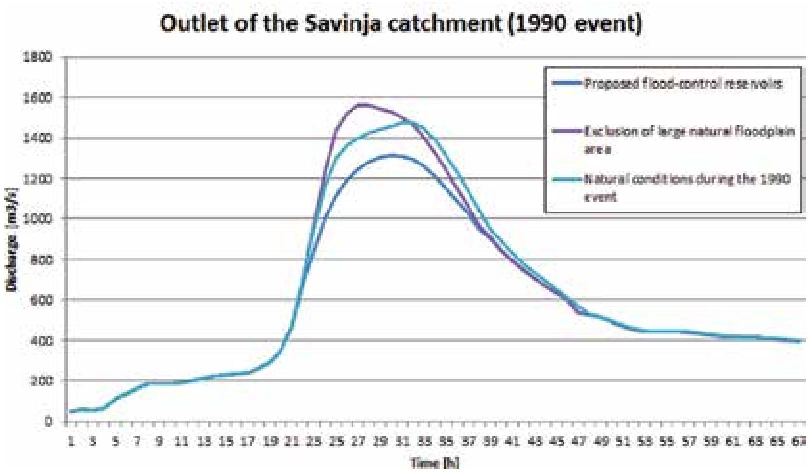

Figure 12. Impact of the proposed flood-control reservoirs with increased total volume (10×10^6 m^3) on the situation at the Savinja outlet during the 1990 flood (dark blue), exclusion of large natural flood area before the Celje city (situation when proposed flood-control reservoirs fail to operate, purple) and actual situation during the 1990 flood (light blue).

Moreover, several smaller flood protection measures (e.g. channel widening at critical cross sections, river banks' reconstruction, local level construction) are also proposed in the Savinja catchment (mostly on rivers Ložnica, Hudinja and Voglajna). The analyses of these measures showed that they mostly positively influence the flood situation at the confluence of Savinja and Sava Rivers. Flood protection measures mostly fasten the hydrograph propagation but often do not significantly influence the peak discharge values (the decrease in the peak discharge is, in most cases, smaller than 1 or 2%). The analysis of catastrophic past flood events demonstrated that the peak discharge on the Savinja River mostly occurs before the peak discharge on the Sava River (**Figure 13**). Thus, faster hydrograph propagation has a positive

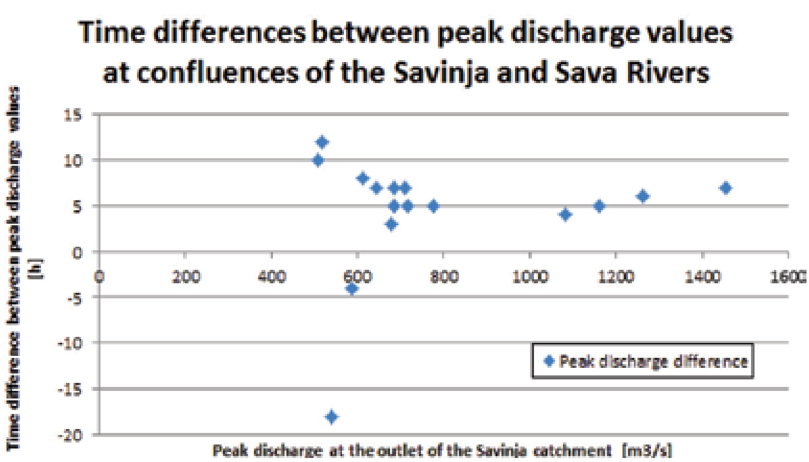

Figure 13. Analysis of time differences between peak discharge values at the confluence of the Savinja and Sava Rivers. Positive values indicate that peak discharge of the Savinja River occurs before the peak discharge of the Sava River.

influence on the situation in the lower Sava River. This kind of local measures mostly have minor impact on the global situation in the larger catchment such as the Savinja River catchment but can lead to improved situation locally. Similar conclusions were also made for the case study of the alpine Inn River in Austria [17].

Furthermore, several other aspects of the flood safety such as the impact of high waters at the river confluences on the downstream flood safety were also investigated but are not discussed in this chapter.

3.4. Backwater effect

Using the calibrated and validated combined hydrological (HBV-light) and hydraulic (HEC-RAS 5) models, we investigated the influence of the proposed flood protection measures (e.g. several flood-control reservoirs are to be built in the large natural flood area before the Celje city) on the flood safety. Moreover, using the hydraulic model HEC-RAS that is presented in Section 3.2, we also investigated the backwater effect on different tributaries in the Savinja catchment. **Figure 14** shows an example of the backwater effect on the Ložnica River. It can be seen that due to the increased peak discharge on the Savinja River, the maximum water on the Ložnica River also increases. This increase is the largest for the cross section located near the rivers' confluence (about 0.6 m for peak discharge increase at 400 m^3/s) and generally, decreases for upstream river station. Moreover, the backwater effect is detected for the cross section that is located 1.5 km upstream of the confluence of the Savinja and Ložnica Rivers. Similar analysis was performed for other rivers (e.g. Hudinja and Voglajna; Voglajna and Savinja). The backwater effect can be up to 0.25 m for a peak discharge of 1000 m^3/s. This kind of analysis can be very useful also for the policy makers because it is essential to understand

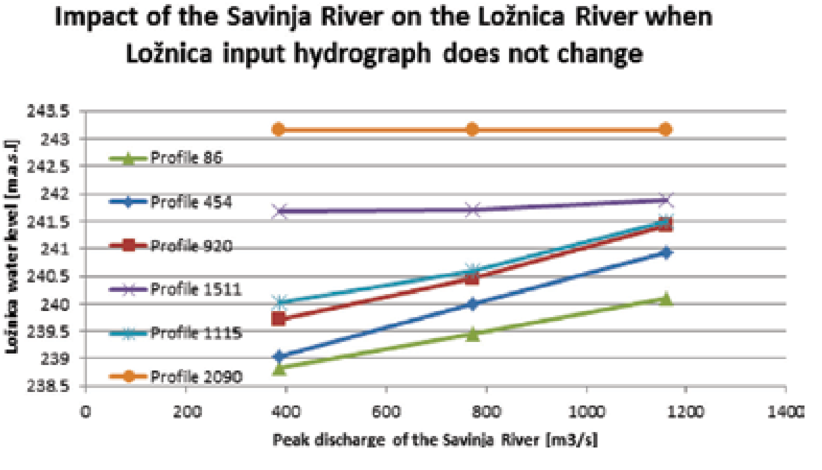

Figure 14. The influence of the Savinja River on the Ložnica River (backwater effect) when the Ložnica input hydrograph is constant during different hydraulic model runs. Different coloured lines represent different cross sections on the Ložnica River where the number indicates river station from the confluence with the Savinja River upstream [m].

that some local measure can also have significant impact on the upstream flood conditions and also on the flood situation at the upstream tributary.

4. Conclusions

In this chapter, combined hydrological and hydraulic modelling was performed in order to investigate the influence of the proposed flood protection measures on the flood safety in the Savinja catchment and in the lower Sava River catchment in Slovenia. The main conclusions are: (1) some of the proposed flood protection measures have positive influence on the flood situation in the Savinja catchment and also at the confluence with the Sava River (either faster hydrograph propagation or peak discharge maximum water level reduction); (2) the main flood protection measures (several flood-control reservoirs) are to be built in the natural large floodplain area before the Celje city and potential problems with operation (or some other problems such as increased sediment transport at the reservoirs inflow) of these reservoirs would lead to the flood safety decrease; and (3) backwater effect in the Savinja River catchment can have a large impact on the flood safety, for example, the backwater effect at the confluence of Savinja and Ložnica Rivers can be up to 0.25 m at the 1000 m^3/s peak discharge of the Savinja River. These conclusions indicate that (small) local measures do not really play an important role in the global flood situation at the catchment and that some local measure can even worsen the flood situation upstream of the measure location. Therefore, complex models (hydrological and hydraulic) of the entire catchment are needed in order to really understand the flood behaviour and to select the most suitable measure that will have positive impacts on the flood safety. Moreover, the selection of the flood measure should also be in-line with the sustainable flood risk management, which means that environmental, social and economic conditions that are mutually connected should be investigated.

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Chapter 6

Engagement of Local Heroes in Managing Flood Disaster: Lessons Learnt from the 2014 Flood of Kemaman, Terengganu, Malaysia

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Additional information is available at the end of the chapter

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Abstract

There were many lessons learned by the flood disaster that hit the peninsular of Malaysia at the end of 2014. Of particular interest was the success story of good flood management that emerged in Kemaman, Terengganu. This chapter sheds some light on the characteristics that contributed to this success. To enable appreciation of this achievement, a comparison between selected flood-inflicted areas is presented, pointing out the similarity between flood factors that, however, produced differences in flood impact. A post-disaster study, which included analysis of flood reports, site visits (which included the disaster site, flood command centre and relief centres) and interviews with those involved in the flood incident, was conducted. The findings revealed the use of technology, a good standard operating procedure and engagement of the local community to be key ingredients of its successful outcome. The study recommends the success of Kemaman to inspire flood management practice for other non-urban flood districts in Malaysia.

Keywords: flood, community engagement, standard operating procedure, district disaster management

1. Introduction

Climate change has brought extreme and uncertain global weather conditions. For Malaysia, this means worsening and hard-to-predict flood disasters. When flood disaster strikes, one can only hope that rescue and relief aid arrive quickly, therefore reducing the impact of the situation. In the 2014 flood incident, impacts were seen to be comparatively less serious for areas where preparation was heightened before, during and after the flood event.

This chapter investigates flood preparation and management of the major flood event that struck the country in December 2014. Interest lies in gaining an understanding of why and how the district of Kemaman was able to report a less serious impact despite undergoing weather conditions similar to other flood-plagued districts. Findings point to the use of technology, procedures and processes, and the engagement of locals during the response and relief phases. The management of flooding in Malaysia typically goes through the following phases: prediction – warning – emergency relief – rehabilitation – reconstruction. The study shows how the local community was involved in making significant contributions in providing prompt responses during a flood, which in this study is based on the case of Kemaman, Malaysia.

Section 2 of the chapter explains the formulation that led to the "worst" flood – the supermoon, monsoon, shoreline and rivers. This is important to establish that the flood districts within the states of Kelantan, Terengganu and Pahang have indeed shared similar flood factors. Then, comparisons of impacts experienced by selected districts are highlighted. Recounts of the events are collected from site visits, reports by the Malaysian National Security Council, news media and social media.

In Section 3, the success story emerging from the flood management (FM) practice in Kemaman is presented. Central to the story is the active and positive roles of local leaders and people from the district. A post-disaster investigation to probe into the engagement of the local community found that early engagement, which started with FM awareness and training, helped empower the locals, who have the advantage of speaking the dialect and understanding the topographies, making them ideal flood emergency responders and volunteers.

2. The 2014 flood

The Peninsular of Malaysia has a long shoreline with its east coast facing the South China Sea, and most of its major cities located near the coast. In addition, there are at least 26 major rivers from 3 states in Malaysia, namely Kelantan, Terengganu and Pahang, flowing from the east coast into the South China Sea, as seen in **Figure 1**.

Frequent flooding over extended periods is considered to be the most natural hazard in Malaysia and affects a large number of the population over a wide area, causing socioeconomic damage. Based on the information published by the Ministry of Natural Resources and Environment, Malaysia, in June 2007, Malaysia has experienced major floods since 1920, especially in the years 1926, 1963, 1965, 1967, 1969, 1971, 1973, 1979, 1983, 1988, 1993, 1998, 2005, December 2006 and January 2007, 2010 and the most recent one in 2014 [1]. These flood events occurred in various states, including Terengganu and the capital city of Malaysia, Kuala Lumpur. This can be seen in **Table 1**, which lists the date of the major floods and the losses incurred by them.

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Figure 1. The three states affected by the 2014 flood.

Date/year	Incident	Property, materials, crops or other losses (MYR)	Number of deaths	Source
1926	Flood known as "The Storm Forest Flood"	Thousands of hectares of forests destroyed	N/A	Chan [2]
December 1996	Floods caused by Tropical Storm Greg in Keningau (Sabah)	300 million	241	
2000	Floods caused by heavy rains in Kelantan and Terengganu	Millions	15	
December 2004	Asian tsunami	Millions	68	
December 2006 and January 2007	Floods in Johor	489 million	18	
2008	Floods in Johor	21.19 million	28	
2010	Floods in Kedah and Perlis	8.48 million	4	
2014	Floods in Kelantan, Terengganu and Pahang	2.9 billion	21	The Star [3]

Table 1. Flood history in Malaysia.

The 2014 flood affected most of the states on the east coast of Peninsular Malaysia due to the northeast monsoon that occurs between October and March every year. These states receive heavy rainfall, which leads to severe flooding almost every year, including the months of November and December 2014. The flood that occurred at the Kemaman area of Terengganu was due to a combination of physical factors, including high tides and elevation. The flood factor of high tides in 2014 was also made worse by the supermoon phenomenon, which is known to change the level of sea tides. When the supermoon is combined with the topographic conditions of the east coast in Malaysia, which has several rivers along the shoreline of these states, it has the potential to aggravate the monsoon flood that occurs annually during the monsoon season. The supermoon effect that was compounded by the northeast monsoon impact in that year brought about a notably higher and prolonged tidal level. These three factors – (1) the supermoon phenomenon, (2) the topographic conditions of Malaysia and (3) the monsoon season – have formulated the worst flood Malaysia has seen in almost 100 years, which is referred to **Table 1**. The first flood was recorded in 1926, and the magnitude of losses can be seen to increase every year, especially the flood of 2014.

The basic cause of river flooding is the incidence of heavy rainfall (monsoon or convective) and the resultant large concentration of runoff, which exceeds river channel capacity [1]. Floods have resulted in huge losses of millions of dollars in Malaysia. For example, the 2014 flood that hit Terengganu and many other states caused more than MYR 2.9 billion (about USD 0.74 billion) worth of damage and hence was deemed the most expensive flood event ever to occur in Malaysian history. This included the cost of damage to infrastructures, property damage, crop loss, disruption to day-to-day services and healthcare expenses. During this flood event, 21 deaths were reported and around 200,000 people were evacuated from their homes and sheltered in relief centres.

The monsoon season of 2014 was marked by torrential rains that began on 17 December. It was followed by non-stop, heavy rain that lasted for three days, 21–23 December 2014, which charted a record-setting rainfall of 1295 mm, equivalent to the amount of rain usually collected in a span of 64 days. The three main rivers of Kelantan – Galas, Lebir and Kelantan – rose drastically above dangerous water levels, which can be seen in **Table 2**.

State	Victims	Area/location	Level during flood	Safe level
Kelantan	31,441	Tangga Krai, Sungai Kelantan	34.11 m	25 m
		Tambatan Diraja	6.88 m	5 m
		Sungai Golok, Rantau Panjang	10.41 m	9 m
Terengganu	32,736	Sungai Kemaman	37.6 m	36 m
Perak	7774	Tasik Temengor, Hulu Perak	247.69 m	Alert level
		Sungai Selama, Selama	14.86 m	Alert level
Johor	328		N/A	
Pahang	29,423		N/A	

Table 2. Report for December 29, 2014.

The rising water levels from the 3 main rivers in Kelantan caused 16 roads in 6 districts to be closed. While in Terengganu, 15 roads in 5 districts were closed. The closing of major roads slowed down the rescue activities because rescue teams had difficulty in reaching the victims due to limited access and resources (boats and helicopters). The main utility provider of Malaysia, Tenaga Nasional Berhad, also suspended the electricity supply because the flood might cause damage to, and it was dangerous to operate, electricity substations in affected states. The majority of properties were submerged by the flood waters in the three states. The second option of transportation to deliver relief was also affected because several Keretapi Tanah Melayu (KTM) intercity train services along the east coast route were interrupted due to the rising water levels on the train tracks. Based on the report by the National Security Council, Terengganu had the most evacuees estimated at 32,736 people, followed by the other states in Malaysia as shown in **Table 2**.

Flooding was the imminent impact for all the states that were situated in the northeast of Malaysia, along the shoreline of the South China Sea. Terengganu, however, reported a less serious impact despite being one of the states situated next to the shoreline.

The impact of the flood in Terengganu was much less notable compared to Kelantan and Pahang. The success of the milder impact in Terengganu can be attributed to two factors: the unique FM system that was implemented specifically in Kemaman and the standard operating procedure (SOP) that was used throughout the disaster. Both of these factors are the main difference between how Kemaman and the other states managed the 2014 flood.

The unique FM system in Kemaman relied on both technology and process to ensure an effective and efficient FM system that could be used by all disaster agencies as well as the public directly impacted by the flood. Kemaman also critically depended on its own SOP, which is annually refined and improved after every flood.

Kemaman flood's workforce starts as early as the first quarter of each year, and includes the establishment of a flood management committee and evacuation centres. Both the committees and the evacuation centres are being championed and joined by local people. The participation of these committees involves the district officer, the local head of the village, and the evacuation centres' chairperson. The creation of the SOP pertaining specifically to the flood, which includes roles and responsibilities of the members of the committee, is the collaborative effort of the local government and local people.

The establishment of the FM system and SOP has helped Kemaman to successfully manage its flood effectively compared with the other states.

3. 2014 Kemaman flood management: a success story

Kemaman is successful in FM plan implementation as compared to Kelantan. This is due to the engagement of local leaders in FM plan implementation. The FM plan is one of the outcomes from the established FM system in Malaysia that outlines the participation of multiple agencies with shared objectives, while performing different activities in managing floods. The FM plan consists of tasks, roles and responsibilities of each agency as well as types of information that should be shared across agencies. Local leaders are considered as one of the entities in the FM plan that has been given its own set of tasks, roles and responsibilities and information, which is sent to the agencies to reduce the effects of floods in their areas or villages.

Section 3.1 provides an overview of the implementation of the FM plan in the state of Kelantan and the district of Kemaman, Terengganu.

3.1. The state of Kelantan

The 2014 flood, which affected 70% of the villages or nearly half of the state population [4], was claimed to be the worst flood recorded in the history of Kelantan [5]. This flood was known as *bah kuning* (yellow flood) due its high mud content [6, 7]. As reported by [8], Kelantan was the worst affected state, which recorded 14 deaths and more than 158,000 victims displaced. Sixteen roads in six districts were closed due to the uncontrolled water flowing from the rivers: Sungai Lebir, Sungai Kelantan and Sungai Golok. The torrential rain, which started on 17 December 2014, caused flash floods and affected 3390 people in Kuala Krai [6]. The continuous rain from 21 December to 23 December in Gua Musang resulted in a rise of water in three major rivers in Kelantan, Sungai galas, Sungai Lebir and Sungai Kelantan, to dangerous levels [8]

The aggravated flood was attributed to the change in climate pattern, adverse weather effects, uncontrolled land management and deforestation and exploitation of land resources [4]. Additionally, a government minister added that unsuccessful implementation of the SOP was the major contributing factor to the crisis in Kelantan [4]. **Figure 2** Shows one of the views of the Kelantan flood in 2014

3.2. The case of Kemaman

Terengganu, a south neighbouring state of Kelantan, despite suffering the same elements of nature, experienced a milder impact. Kemaman, a district in the state of Terengganu, due to its geographical location and landscape, has considered flooding as a common phenomenon.

Figure 2. View of Kelantan flood in 2014.

More than 34,000 victims in the district were evacuated during the flood of 2014. The milder impacts were partly attributed to having a good operating procedure and the involvement of the local community. **Figure 3** shows one of the views of the Kemaman flood in 2014.

3.3. Operating procedure

The SOP in FM, which was implemented by the district, was awarded a gold standard for acknowledging its success in organising and implementing FM plans during the 2014 flood [9]. The objectives of the SOP are to act as a main reference for FM in Kemaman, as a basis to improve the FM-related process and to create a system involving the public (including students) to play a role in assisting the victims and to identify resources and risks in FM. The SOP has outlined the organisational structures (membership) in FM from district officer level to committee level, workflow for each of the FM phases (before flood, during flood, after flood), clear roles and responsibilities for each of the committees, cross-agency coordination through well-defined relationships with other responding agencies, information sharing processes, resource management and risk management. The SOP elaborates the mechanism to respond to flood, which includes:

- **i.** Identification of places for the stranded community such as mosques.
- **ii.** Information sharing with the affected community through pamphlets, announcement at the mosque before prayer and displaying information on the community hall notice board.
- **iii.** Sharing of resources across agencies such as telecommunication devices (Government Integrated Radio Network (GIRN) and walkie-talkies).
- **iv.** Partnership with private telecommunication companies to elevate the communication equipment cabinet at the communication signal transmitter site.
- **v.** Information sharing across agencies using applications such as WhatsApp and Telegram.

Figure 3. View of Kemaman flood in 2014 (source: Astro Awani, 2014).

vi. Well-planned measures to minimise the identified FM risk, for example, walkie-talkies and GIRN are used in case of disruption to the telecommunication signal.

vii. Emphasis of community involvement in the document. The flood simulation activity includes the roles and responsibilities of the village development and security committee in FM.

3.4. People

According to Dr. Sharifah Zarah Syed Ahmad [10], Secretary at the Ministry of Communications and Multimedia, there were several contributing factors for the successful implementation of the FM plan in Kemaman. The success story of Kemaman was due to collaboration with the public such as local leaders. During the preflood preparation phase, a flood central committee, which comprises representatives from each of the constituencies in Kemaman, was deployed. The constituencies decided on the location of the main relief centre and have involved the public in the flood awareness campaign.

The people of Kemaman are well equipped with knowledge of how to respond to disaster. Information pertaining to the relief centre location, flood kits and actions in responding to disaster (before, during and after) was imparted to the people either verbally or via pamphlets. The address of the GPS coordinate to assist helicopters to land was identified based on the advice from local leaders. The helipad location is crucial to ensure the army can send and pick up supplies for victims. The rapid dissemination of information was aided by the utilisation of information and communication technology. The people are aware of the flood early warning routine and react quickly according to the plan. Text messages were sent to the people estimating the time that the flood would arrive at the identified locations. As such, the local community could respond to the effects of flooding by saving important documents and evacuating to the identified relief centre.

From the case of Kelantan and Kemaman, it can be noted that local leaders' enrolment is crucial for the successful implementation of the FM plan. The local leaders help to inculcate awareness among their community for timely response during flooding. The dissemination of information between local leaders and the community is essential for speedy action in the event of a flood.

4. The "local heroes" elements

The 2014 flood event was an unpredicted disaster. The fast rising water level claimed many acres in a matter of minutes. Orders soon came from officials regarding the evacuation of thousands of residents and the opening and closing of shelters as flood water inundated and ravaged towns, roads, villages and homes. In issuing directions to the mainly local people (villagers), someone who understands the local language and area would be the ideal choice. Apparently, in the rescue and relief of people in Kemaman, a number of heroes emerged: the assemblyman, the district authorities, the headman and the village community committee were all identified as local heroes.

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Local heroes in the context of Kemaman would be persons with knowledge of the local areas and those who clearly understood the disaster situation as well as directly responding to the unpredictable conditions based on their experience. In the opinion of others, local heroes possess special achievements, abilities or personal qualities and are regarded as role models or ideal leaders to take charge during a flood. The involvement of local people along with the local authorities has established the Kemaman SOP as an outstanding procedure to be followed compared with other districts. **Figure 4** illustrates the information exchange and collaboration

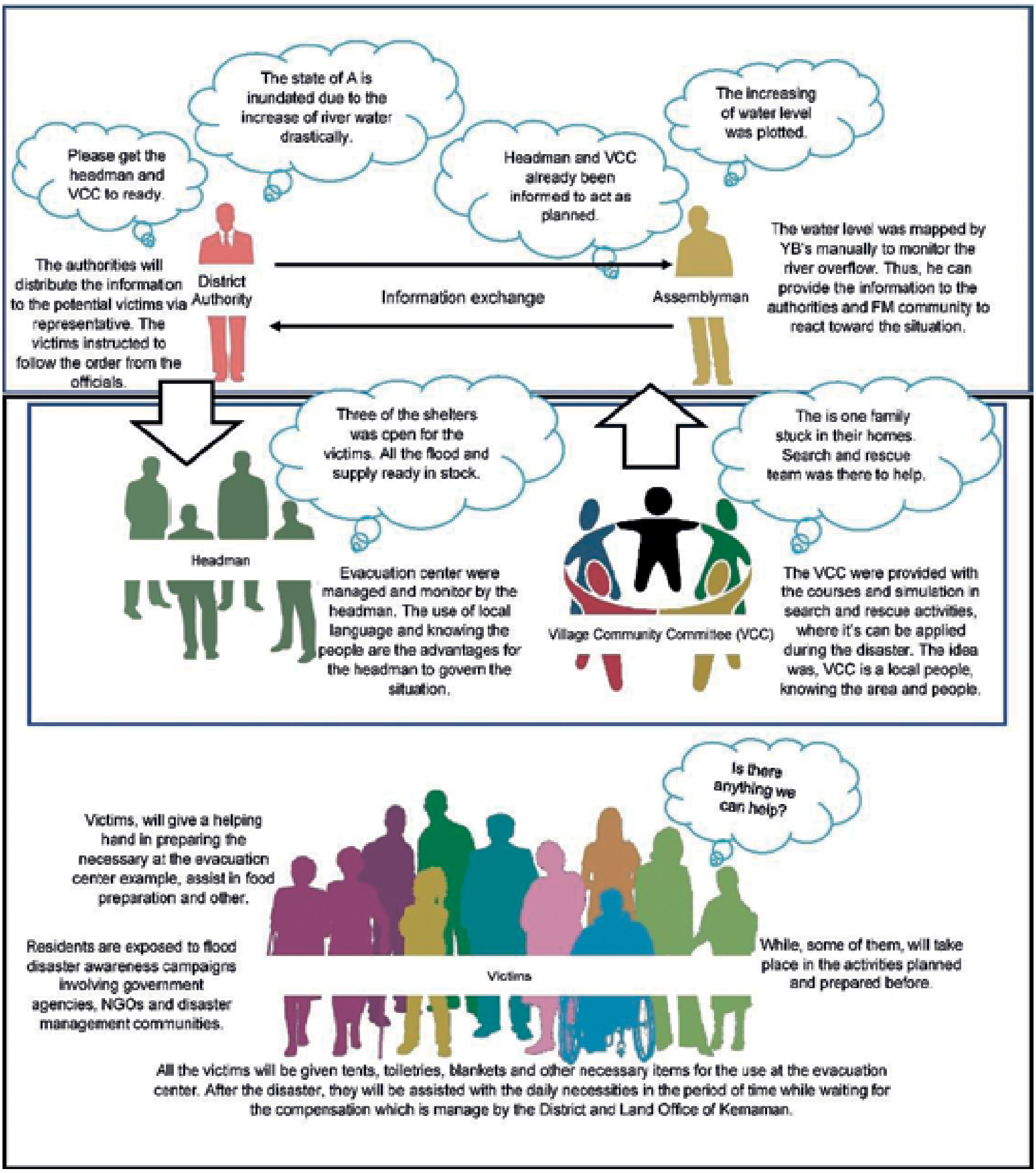

Figure 4. Information exchange and coordination between the local heroes in the case of the 2014 flood at Kemaman.

among local heroes, together with an explanation of the preparation and implementation of the flood event, that were championed by those at Kemaman, Terengganu, during the 2014 flood.

4.1. Local heroes

As mentioned earlier, a local hero is someone who has extensive local knowledge of the flood operating procedures. Evidence of this can be seen from the well-drawn map that was produced by the assemblyman, which was used to estimate the arrival of the flood. This map was produced based on his knowledge of and familiarity with the river basin, all of which has contributed to easier flood management in the Kemaman district. An assemblyman in Malaysia is an elected representative from single-member constituencies during state elections, voted by local people from their constituencies.

Figure 5 shows the assemblyman's personal sketch estimating the speed and arrival of the flood to the main road. The assemblyman drew the map as a guide in planning for the evacuation, rather than relying on technology because of inaccurate information provided by the system (inaccuracy may be caused by rapid changes in sedimentation or rate of rise of the flood water). The purpose of the sketch is to monitor the villages as well as the speed of the river water, which helps the FM agencies provide instructions to evacuate victims from flood areas.

FM also had problems in delivering food and supplies to the affected flood victims. The assemblyman believed that food and supplies should be ready in advance of the flood because it can be chaotic to deliver and distribute them during a flood. Thus, Kemaman District Office had reviewed the Kemaman District Disaster Management Committee by involving the headman in their process of managing the flood. In the engagement of local heroes during the flood in Kemaman, the headman of every village is considered to be the second most important leader after the assemblyman. The headman is responsible for monitoring the process in evacuation centres and food and supply depots.

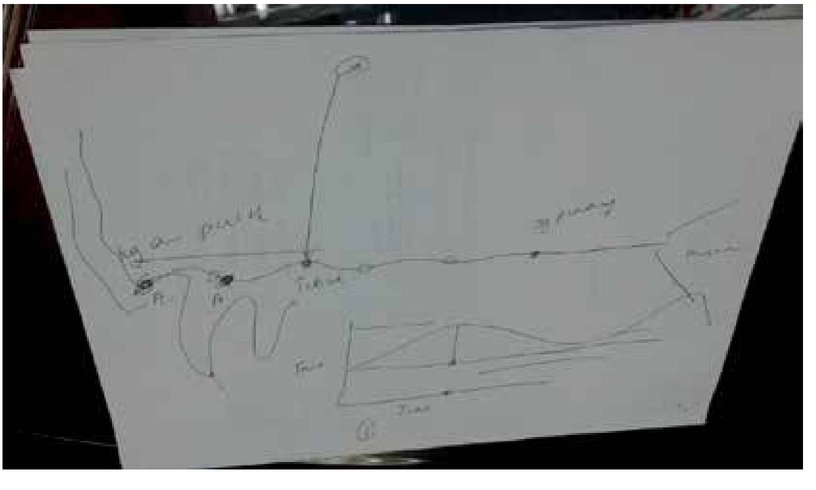

Figure 5. Assemblyman's personal sketch.

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Figures 6 and **7** show the depot with the food and supplies prepared by the Kemaman District Office. The supplies collected were kept at the Air Putih depot and these must be ready before the flood so that the management can focus more on the search and rescue activities once the flood hits. The headman was considered as the leader in the evacuation centre since he understood and knew the residents, and this helped to ensure that the information was delivered faster and easier.

Figure 8 shows the involvement of headmen and the members from the village community committee in the Kemaman District Disaster Management Committee that was established by Kemaman District and Land Office in managing the 2014 flood. Disaster awareness and simulation programmes were provided to the headmen and members of the village community committee. The aim of this activity was to familiarise and prepare the headmen to manage the disaster and provide relief to the victims and others on how to respond to a disaster.

Involvement of headmen and members of the village community committee.

Figure 6. Air Putih food and supply depot.

Figure 7. Food and supplies were prepared at the Air Putih depot for seven days.

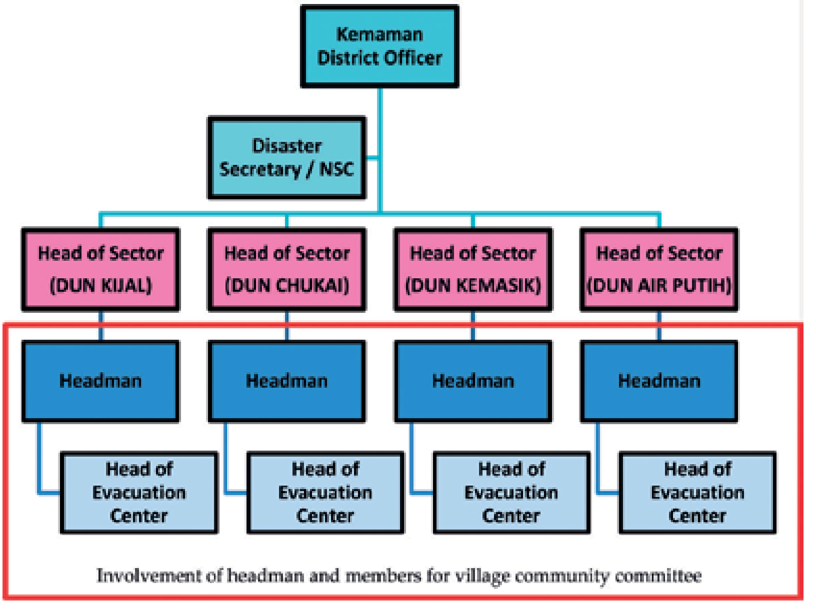

Figure 8. Kemaman District Disaster Management Committee. Note: National Security Council (NSC)

Figure 9 shows the boat operation course and water survival simulation conducted by Kemaman District and Land Office that involved the headmen, local people and government agencies. The simulation exercise aimed to provide exposure to the person responsible for the search and rescue of flood victims, which was the preliminary planning of the Kemaman authorities, in ensuring that pilot actions have been taken and prepared with any possible occurrence.

Kemaman also practises the concept of transformational leadership known as on-scene leadership, which allows the responsible person to spontaneously act as leader and give instructions

Figure 9. Boat operation course and water survival simulation.

regarding unexpected changes during the disaster due to rapid environmental changes. This strategy was aimed at reducing the impact of the flood, where any local leaders involved can become a leader for the district when the flood hits.

4.2. Benefits of having local heroes

By having local heroes to oversee the flood management activities, Kemaman SOP managed to obtain a "gold standard" as announced by the Malaysia Prime Minister and published in Bernama, December 31, 2014. Local heroes are at an advantage since they understand the problems of residents, know them personally and have great knowledge of the local area. Local heroes have better understanding and greater knowledge with a clear picture of problems that may occur due to heavy rains and flooding. Floods are sometimes accompanied by a number of problems that need to be solved by the leaders. Because a local hero is the most knowledgeable person to identify the problems that arise and the extent to which they can occur, they need to find solutions to all the problems and ensure that the flood can be managed efficiently.

Having knowledge of the culture of people and places was another advantage that Kemaman local heroes possessed in governing the 2014 flood. Kemaman District Disaster Management applied the concept of giving priorities to special people, which included any ailing person, disabled person orang kurang upaya (OKU), pregnant women and people living far away from the evacuation centre. These categories of people were prioritised during the evacuation process. Information regarding the victims that fit the categories to be prioritised was gathered from the information system used at the Kemaman District Office.

A high level of understanding of the dialects used by the locals was also an advantage in the management of the 2014 flood in Kemaman. The understanding of local dialects helps because information can be communicated easily, quickly and accurately to people who are exposed to floods. It also facilitates the population to act on the instructions issued by the authorities.

5. Conclusion

A warmer atmosphere brought by climate change will result in increased precipitation or water vapour. For Malaysia, which lies in a wet region, this means heavier rainfall rates. The growth in population (and development), which dictates changes in land use to support their needs, has also increased the severity of flood disaster. As such, improvement over methods for flood governance and management has become even more important. Lessons garnered from the big flood of 2014 must be quickly translated into actionable items for managing future floods, especially in the non-urban areas in Malaysia.

Use of information technology combined with mobile apps and social media for data collection and storage, information sharing and decision making by the Kemaman flood team have only become successful due to the commitment of everyone involved to diligently participate in the development, training and simulation of flood protection, and providing feedback for improvement. Likewise, in the development of the Kemaman SOP (dubbed the gold standard SOP), the SOP was successful partly due to the awareness programmes and training drills to ensure that it was understood and executable.

Last but not least, engagement of the local community was one of the key ingredients to success. Technological sophistication will not, at least in the near future, match the effectiveness of a familiar "local" hero – one who understands the local dialect, remembers the topography (landmarks and such) by heart when road signage becomes unreliable and knows the community members and neighbours.

Considering the above, it is suggested that the flood governance and management platform be developed to engage the local community.

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Chapter 7

Sustainable Groundwater Management in Context of Climate Change in Northwest Bangladesh

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Additional information is available at the end of the chapter

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Abstract

The objectives of the study are to understand the variability and changes in hydroclimatic variables in space and time dimensions, and to evaluate the performance of managed aquifer recharge (MAR) for sustainable water resources management in northwest Bangladesh. The study reveals that groundwater resource in the northwest Bangladesh is under stress. The stress has developed and it increases over the years, as a result, shallow groundwater resource has already become scarce. The people of the area are not getting even drinking water using their hand tube wells (HTWs) during the dry season and facing trouble with irrigation water. These problems are becoming acute as a result of uncontrolled and unplanned groundwater abstraction for irrigation. Moreover, rainfall in the study area decreases and dryness increases. Higher values of the seasonality index ($\overline{SI}$ = 0.87) and precipitation concentration index (PCI = 19.8) are indicators of frequent dry spells. The area suffered from 12 moderate-extreme droughts during 1971–2011, and moderate to high drought risk (B) prevails in the area. The frequent drought, decreasing trend in rainfall, transboundary river flow, and thick clay surface lithology along with the uncontrolled irrigation are also responsible for rapid depletion of groundwater. As the annual surplus of water (average = 594 mm) is higher than groundwater recharge (330 mm), an experimental study on managed aquifer recharge (MAR) has been conducted to enhance the groundwater recharge. It shows good performance for restoring the groundwater without creating any sorts of hazards. Moreover, almost 5% of irrigated land can be irrigated from surface water sources by re-excavating the rivers, *Kharis* (small channels). It is necessary to prepare an integrated water resource management plan (IWRMP) considering the impacts of climate change, drought risk, driving factors of the groundwater resource depletion, and rainwater as a resource for achieving the sustainability.

Keywords: climate change, drought prone area, managed aquifer recharge, sustainable groundwater management

1. Introduction

Water is a vital natural resource and is a key requisite for sustainable development. Groundwater depletion has been recognized as a global problem. The estimated global groundwater depletion during 1900–2008 is about 4500 km^3, and rapid depletion of groundwater has occurred during 2000–2008 [1]. Groundwater withdrawal for irrigation has intensified around the world over the past few decades. This withdrawal has largely occurred without hydrological planning, as a result, a high groundwater depletion has occurred. Therefore, the sustainable management approach has attracted attention to the hydrological community and some concepts have developed. However, Unver [2] pointed out that sustainable development is a concept still in the making as most of the traditional concepts fail to ensure the use of water resources in a sustainable manner. The groundwater footprint concept focuses on groundwater recharge as an index of sustainability [3]. Groundwater recharge rates alone cannot serve to address the core policy question regarding the sustainable aquifer conditions [4]. Studies [4, 5] stated that groundwater management plans based on traditional concepts like safe yield, assured water supply, and groundwater footprints are not clear indicators of groundwater sustainability mainly due to ignoring the impact of climate change and drought. However, water resource is at the core of sustainable development recognized in the Rio World Summit in 1992. United Nation (UN) Sustainable Development Goals Report [6] has emphasized on sustainable management of water resources (Goal-6) and combating climate change impact (Goal-13). Hence, the present study has given the main attention to the sustainability of groundwater resource by integrating drought characteristics, and climate change effects and status of the groundwater resource. Our previous studies [7–9] investigated the groundwater level scenario, drought characteristics, and dynamics of drought in the northwest Bangladesh. However, the impact of climate change on rainfall pattern which is the main source of groundwater recharge and potentiality of surface water resource have not been investigated comprehensively yet. In the present study, rainfall climatology, reanalysis of long-term groundwater level data (1971–2011), driving forces of groundwater depletion, groundwater recharge, and potentiality of surface water resource have been investigated comprehensively. Beside these, an experimental study on managed aquifer recharge (MAR) has been conducted and performance of MAR has been assessed. Therefore, it is expected that the study will contribute to the development of the concepts of sustainable water resources management and understand the phenomena groundwater sustainability in the context of climate change in drought prone areas.

2. Study area

The study area includes Chapai Nawabganj, Naogaon, and Rajshahi districts and covers 25 Upazilas (sub-district) in the northwest Bangladesh (**Figure 1**). The area is popularly known as Barind area and the area covers approximately 7545.25 km^2. Geographically, the area extends from 24°08′ to 25°13′N latitudes and from 88°01′ to 89°10′E longitudes. The map of the study area, including the locations of rain gauge stations, meteorological stations, groundwater observation wells, vertical electrical sounding (VES) stations, and managed aquifer recharge

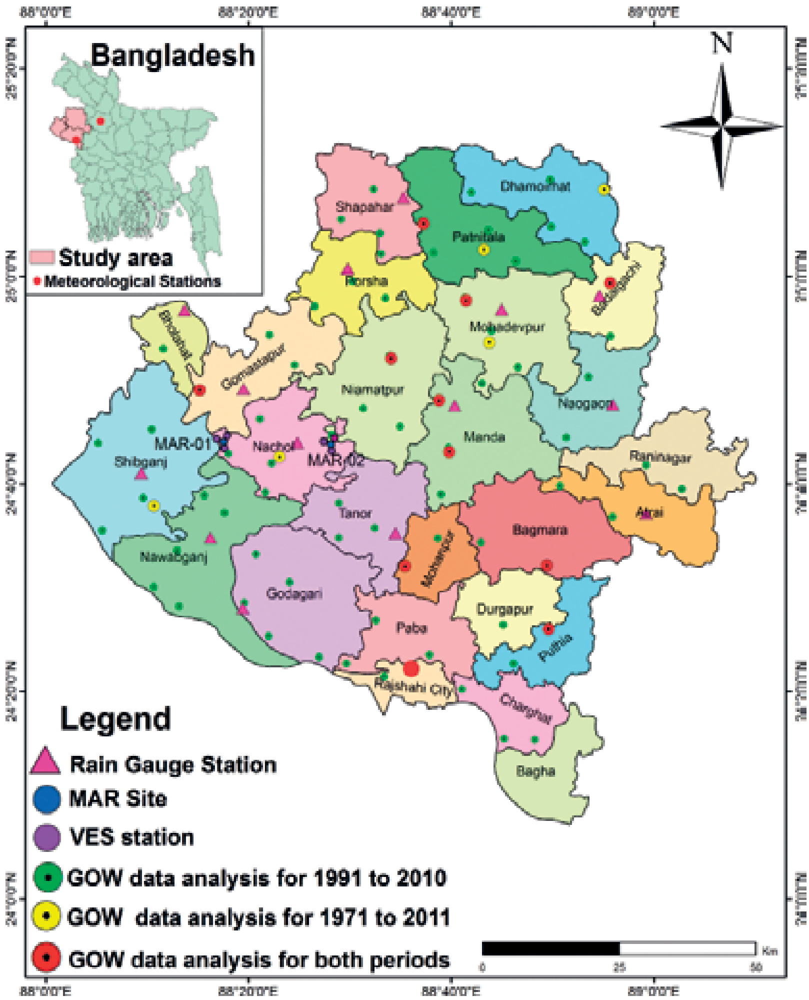

Figure 1. Study area with locations of meteorological, rain gauge, and VES stations, groundwater observation wells (GOW) and MAR sites.

(MAR) sites, is shown in **Figure 1**. Groundwater is the main source of irrigation in the agro-based northwest Bangladesh and Barind Multipurpose Development Authority (BMDA) is responsible for irrigation water management. Groundwater resource exploration is ongoing on the basis of one-third rainfall recharge hypothesis of BMDA that is beyond the sustainable yield [10]. About 75% of the land in the study area is used for agricultural practices. High yield variety (HYV) *Boro* rice, which cultivates during the dry season completely depends on groundwater irrigation, shares almost 81.2% of the total cultivable area.

2.1. Geology and hydrogeology

The physiographic features of the area are mainly two types. These are (1) Floodplains which include Tista, Lower Purnabhaba, Mahananda and Ganges flood plains; and (2) Barind Tract

(BT). There exists a significant lithological variation in the BT and the adjacent floodplain areas. BT is comprised of thick clay surface lithology which is underlined by thick coarser sediments of Early Pleistocene to Late Paleocene. The materials are dense and compact, and the hydraulic conductivity of the surface clay layer is low [11]. Two different aquifer units have been identified based on hydro-stratigraphic data in the area [11]. The upper-shallow aquifer exists just beneath thick surface silty clay layer. The thickness of this aquifer ranges from 10 to 35 m and it consists of very fine-to-fine sand with lenses of fine to medium sand and occasionally clay, silt, and trace mica lenses. Below the upper-shallow aquifer, there is a lower-shallow aquifer. The thickness of this unit ranges from 20 to 70 m, and it is composed of medium to coarse grain sand with occasional fine sediment lenses.

3. Data and methods

3.1. Data

There are 18 rain gauge stations, including one meteorological station in Rajshahi in the study area. However, 15 stations have long-term (1971–2011) good records (**Figure 1**). Rahman et al. [8] collected rainfall data from the Bangladesh Water Development Board (BWDB) and meteorological data from the Bangladesh Meteorological Department (BMD). The study prepared a complete rainfall dataset by estimating missing values by Multiple Imputations Method. Moreover, data of Bogra meteorological station have also been analyzed as it is located very close to the study area. Details regarding the rainfall data can be found in Rahman et al. [8]. There are about 150 groundwater monitoring wells in the study area. However, only 15 wells have long-term (1971–2011) good records and 73 monitoring stations have good records for the period of 1991–2011 (**Figure 1**). These data have also been collected from the BWDB. Details of groundwater level monitoring data can be found in Rahman et al. [7, 9].

3.2. Methods

Rainfall climatological characteristics, such as rainfall seasonality index, (SI) has been calculated by Walsh and Lawer [12] formula. Time series of seasonality index ($\overline{SI_k}$) and precipitation concentration index (PCI) have been estimated by Pryor and Schoof [13] and Oliver [14] formulas, respectively.

3.2.1. Trend analysis

In the present study, trends have been detected by non-parametric Mann–Kendall [15, 16] (MK) test. MK test shows a good performance for identifying trends in hydrological variable [7–9]. If there is a significant serial correlation at lag-1 in the climatic data, MK test cannot calculate the exact value of test statistic [17]. In the study, lag-1 serial correlation has been evaluated before analyzing the trends. If there is a significant serial correlation at lag-1, the trend free pre-whitening method [17] has been applied to eliminate the influence of serial correlation before estimating the test statistic (Z). Moreover, the sequential values of the MK test have been used [18] to find out the change point. The rate of change has been calculated by Sen's slope estimator [19]. The details of the methods can be found in [7–9, 15–19].

3.2.2. Drought risk ranking

Our previous study characterized the drought in the study area [8] using the standardized precipitation index (SPI) [20]. Drought risk ranking is necessary to prepare the viable adaptation measures of an area. This study has ranked the risk of drought using the drought risk ranking diagram [21] to know the risk condition of the area.

3.2.3. Groundwater recharge and abstraction

The groundwater budget of an area can be written as [22]:

$$R = \Delta S^{gw} + Q^{bf} + ET^{gw} + \left(Q^{gw}_{out} - Q^{gw}_{in}\right) \tag{1}$$

Here, R = recharge; ΔS^{gw} = change in groundwater storage; Q^{bf} = baseflow to river channel; ET^{gw} = evapotranspiration from groundwater, and $Q^{gw}_{out} - Q^{gw}_{in}$ = net subsurface flow from the area. The Q^{bf} and ET^{gw} are negligible for Bangladesh as river stage during the monsoon is higher than the groundwater level and land cover dominated by the shallow rooting depth crops [23]. Moreover, groundwater flow $(Q^{gw}_{out} - Q^{gw}_{in})$ is also negligible due to the absence of substantial hydraulic gradients in water level in shallow aquifer during monsoon [24]. Shamsudduha et al. [23] simplified Eq. (1) and calculated groundwater recharge (R) as:

$$R = \Delta S^{gw} = S_y \frac{\partial h}{\partial t} = S_y \frac{\Delta h}{\Delta t} \tag{2}$$

where, S_y is the specific yield, Δh is the water-level height between annual maxima and minima, and Δt is time period (a year). Eq. (2) is similar to water table fluctuation (WTF) method and recharge is referred as "net" recharge [25]. In WTF method, Δh is the difference between the peak water level and the theoretical lowest level [25]. However, Shamsudduha et al. [23] calculated Δh as an annual range between the annual maxima and minima from weekly measured data. Groundwater recharge calculation using Eq. (2) did not provide good results for recent periods (1985–2007 and 2002–2007) for some particular areas (Dhaka City and BT) as the seasonality in groundwater fluctuation suppressed by the long-term trend associated with intensive abstraction [23]. For these areas in Bangladesh, net groundwater recharge was calculated [23] as:

$$R = \Delta S^{gw} + Q^{P} \tag{3}$$

where Q^P is the annual groundwater abstraction. In the study, groundwater recharge has been calculated by Eq. (3) for the BT. However, Q^P is the groundwater abstraction for supplementary irrigation during the rainy season as a huge amount of groundwater withdrawn during the dry season for *Boro* rice cultivation about 1 m per square meter in Bangladesh [24, 26]. Therefore, adding the annual groundwater abstraction misleading the net recharge calculation.

The groundwater abstraction for irrigation in Bangladesh estimated from the irrigated proportion of the surface area and the amount of water applied to an irrigated field during the growing season [24, 26]. The time series data of the total irrigated area of the greater Rajshahi district, which includes the study area and Natore district, have been collected from the book published by Bangladesh Bureau of Statistics (BBS) for the period of 1993–2010. The groundwater abstraction has been calculated as the irrigated area is multiplied by an estimated 1.0 m [24] of abstraction per pumping season per square meter of irrigated area.

3.2.4. Vertical electric soundings (VES)

Vertical electric soundings (VES) survey following the Schlumberger electrode configuration using a direct current resistivity meter has been carried out in six areas in Nachole Upazila (**Figure 1**) in Chapai Nawabganj district. The VES data has been analyzed using resistivity meter compatible software IGIS 2.0 which follows the inverse slope method for analyzing the resistivity data. Inversion is a mathematical iterative process and study [27] showed that the inverse method is quite a powerful scheme to interpret the resistivity data. Two bore holes have also been done and bore logs data have been used for validation of the lithology interpreted from resistivity data. These bore holes later have been used as MAR wells (**Figure 1**).

4. Results and discussion

4.1. Rainfall climatology

4.1.1. Exploratory statistics

The annual average rainfall in the area during the period 1971–2011 varies from 1326 to 1650 mm with an average of 1505 mm, which is about 39% less than the national average of Bangladesh (2456 mm) [28]. There is a sharp gradient in an increase in rainfall from southwest to northeast (**Figure 2a**). The winter season is very dry and only 2.5% of annual rainfall occurs during this season. After the winter, rainfall starts to increase due to thunderstorms or nor'wester during summer season. During summer, rainfall varies from 192 to 282 mm with an average of 220 mm which is 14.6% of annual rainfall. The rainfall during rainy season varies from 1001 in the southwest to 1370 mm in the northeast. Almost 83% of annual rainfall occurs during this season due to the tropical depressions which enter the country from the Bay of Bengal [29].

4.1.2. Trends in rainfall

4.1.2.1. Annual rainfall

The annual rainfall of the study area during the period of 1971–2011 shows an insignificant decreasing trend ($Z = -0.75$) at a rate of −2.76 mm/year. Trend analysis results of 15 stations indicate both decreasing (53.3%) and increasing (43.7%) trends. However, most of the trends (about 80%) are statistically insignificant. Two significant decreasing trends at 90 and 95%

confidence levels are found in Rajshahi (−8.02 mm/year) and Mohadevpur (−10.82 mm/year) stations, respectively. On the other hand, a significant increasing (+11.17 mm/year) trend is found in Nawabganj at 99% confidence level. The plots of sequential MK test statistics of u(d) and u′(d) (**Figure 3a–c**) indicate downward trends started in 1981 and 1988 in Rajshahi and Mohadevpur, respectively, and significant upward trend in Nawabganj starts in 1991. The spatial distribution of the Z statistic reveals that the declining trend mostly occurred in the eastern part of the area (**Figure 2b**) and magnitude (slope Q) varies from −0.25 to −10.82 mm/year (**Figure 2c**). Significant negative trends are detected in the northeast and southeast. However, the majority of the stations located in the BT shows insignificant positive trends. The projected rainfall of Bangladesh at different emission scenarios shows an increase in rainfall, but the study found decreasing rainfall in Rajshahi [21].

4.1.2.2. Seasonal rainfall

Trend analysis of seasonal rainfall shows a declining trend in rainfall for all seasons. The estimated Z statistics are −0.94, −0.12, and −2.13 for winter, summer, and rainy seasons, respectively. The declining trend in rainy season rainfall in the area is significant at 95% confidence

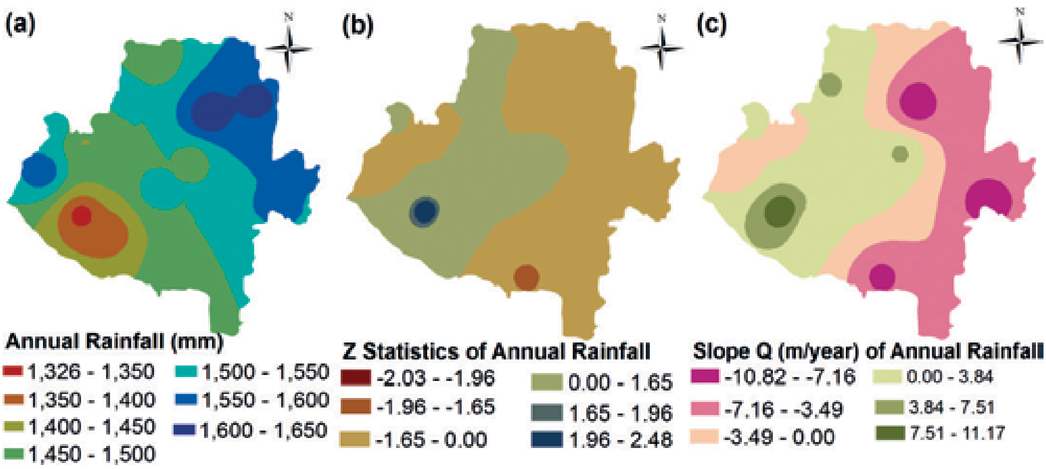

Figure 2. Distribution of (a) annual rainfall, (b) Z statistic of annual rainfall, and (c) Sen's slope (*Q*) of annual rainfall.

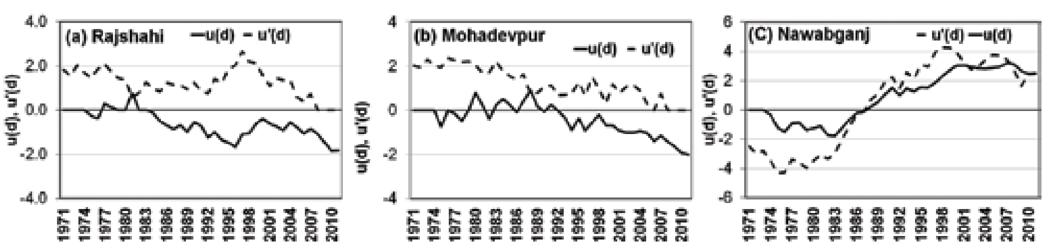

Figure 3. Sequential MK statistic u(d) and u′(d) of annual rainfall (a) Rajshahi, (b) Mohadevpur, and (c) Chapai Nawabganj.

interval. Station wise analysis reveals that most of the trends are insignificant decreasing and accounting for 73.3, 46.67, and 67% of the stations for winter, summer, and rainy season, respectively. The entire study area except the southwestern corner shows a declining trend in winter season rainfall (**Figure 4a** and **b**). In the summer season, insignificant negative trends are found in the eastern part of the area, however, insignificant positive trends are found in the western part (**Figure 4c** and **d**). Insignificant decreasing trends in rainy season rainfall are found in the eastern part, but insignificant rising trends are found in the BT (**Figure 4e**). The slopes of summer and winter seasons are very low (**Figure 4b** and **d**). Rainfall in the BT increases over the years at a rate of less than 3 mm/year (**Figure 4f**) during the rainy season.

4.1.2.3. Monthly rainfall

Monthly rainfall time series indicates the magnitude of change is close to zero for the months of Nov–Feb. All stations, except Sapahar, show increasing trends in rainfall for the month

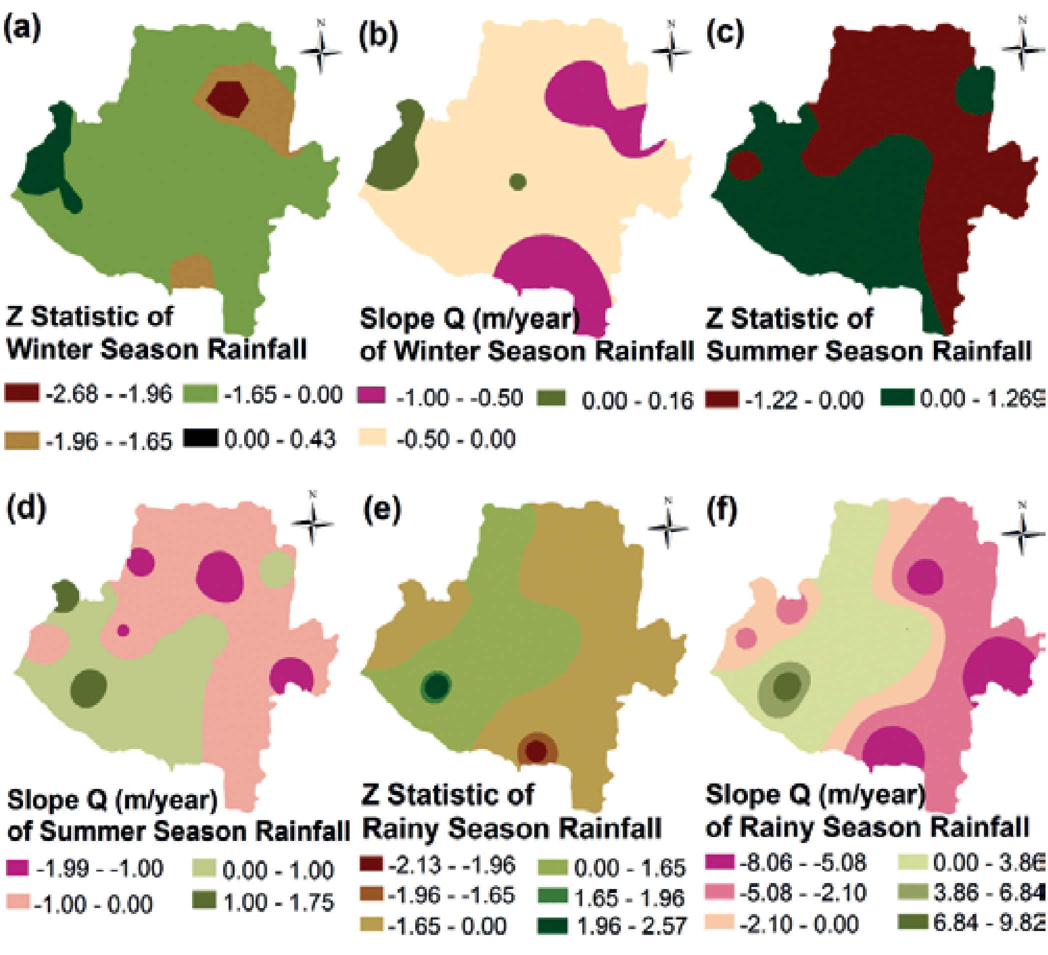

Figure 4. Distribution of Z statistic and slope (*Q*, mm/year) of seasonal rainfall.

of March and Nachole shows a significant increasing trend. There are no significant trends in rainfall for the months of April and May. Insignificant increasing trends except Atrai are found in rainfall in June. However, the decreasing trends except Nawabganj are found in July rainfall and significant trends found in Rohonpur, Badalgachi, Mohadevpur, and Sapahar. The magnitudes of changes of the significant trends range from −3.90 mm/year in Badalgachi to −5.76 mm/year in Sapahar. Insignificant decreasing trends are found in rainfall of 11 stations in August and September. The decreasing trends also dominate over the area in October rainfall. The overall findings show rainfall in the middle of the monsoon decreases.

4.1.3. Seasonality index (SI) and precipitation concentration index

SI value in the study area varies from 0.84 to 0.89 (**Figure 5a**) with an average of 0.87, which indicates rainfall is markedly seasonal with a long dry season. The Z statistic of seasonality index (SIk) time series (**Figure 5b**) indicates an insignificant trend dominated over the area. The PCI calculated on an annual scale varies from 18.26 in Rajshahi to 20.42 in Bholahat with an average of 19.84 (**Figure 5c**). In general, lower values are found in the BT, whereas higher

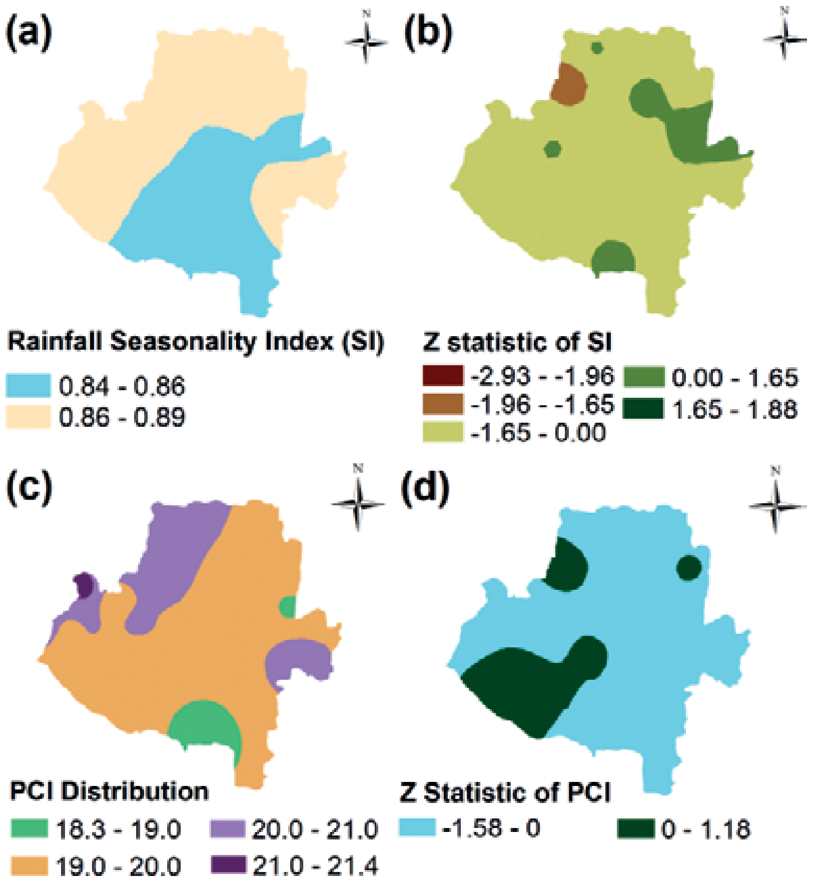

Figure 5. Distribution of (a) rainfall seasonality index (SI), (b) Z statistic of SI, (c) PCI, and (d) Z statistic of PCI.

values are found in the northwestern part (**Figure 5c**). The PCI value indicates irregular to strong irregular distribution of rainfall over the area. High PCI value also indicates a higher percentage of annual total rainfall occurs within a few rainy days, as a result, the area suffers from frequent drought. The distribution of the Z statistic (−1.58 to 1.18) of the MK test of PCI indicates an insignificant negative trend dominates over the study area (**Figure 5d**).

4.1.4. Drought characteristics

The details of drought characteristics of the area have been discussed in Rahman et al. [8]. The area suffered from 12 moderate to extreme droughts during the period of 1971–2011. Almost 75% of drought events in the area associated with El Niño. Southern and central parts of the area frequently suffer from severe to extreme hydrological droughts, whereas the northern part suffers from agricultural drought. The trend analysis of the SPI indicates dryness in the area increases [8]. The drought risk ranking diagram has been prepared to know the risk condition of the area. In the risk ranking diagram, the frequency has been plotted on the vertical axis and classified into four classes as high (one event in 3 years); moderate (one in 3–5 years); low (one in 5–10 years); and very low (one after 10 years) [21]. SPI drought classification [20] has been used to classify the drought and plotted on the horizontal axis. Risk is classified as A (high), B (moderate to high), C (sufficiently high), and D (low) [21]. Agricultural, meteorological, and hydrological drought risks conditions of the area have been presented in **Figure 6**. The severity of mild drought is the lowest among the four categories, but frequency is high. Hence, risk associated with mild drought is sufficiently high (Class C). The risk associated with moderate agricultural and meteorological droughts is low (Class D), however, it is sufficiently high (Class C) for hydrological drought. The drought risk condition is moderate to high (Class B) for severe drought in the study area. It is also moderate to high (Class B) for extreme hydrological and agricultural droughts. The rain feed *Aman* paddy cultivates over the area; the frequent mild and moderate droughts cause damage to the crop production. Severe drought can cause more than 40% damage to rice production [21]. Our field study reveals that during the last drought period (2008–2010), farmers of the area frequently irrigated the paddy field to minimize the loss of rice production as a result rapid depletion of groundwater occurred.

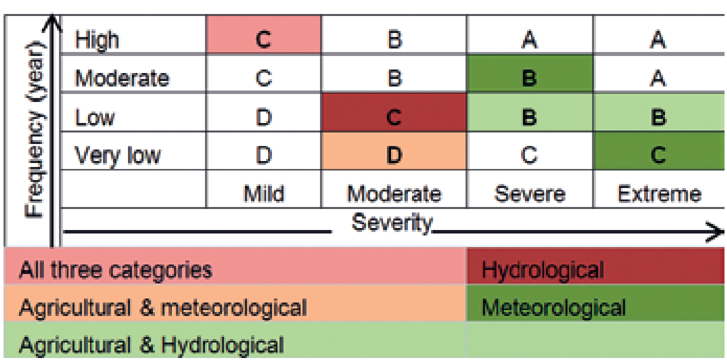

Figure 6. Drought risk ranking based on frequency and severity.

4.1.5. Water balance

PET has been calculated by Penman-Monteith equation [30]. The concept of water balance in the unsaturated zone [31] has been applied to calculate actual evapotranspiration (AET), annual deficit and annual surplus of water. This combination produced better results for the water balance study of Bangladesh [32]. PET has been calculated for two meteorological stations like Rajshahi (1378 mm) and Bogra (1327 mm). The AET varies from 875 to 955 mm with an average of 914 mm which is about 62% of annual rainfall. Annual surplus amount of water varies from 448 to 759 mm (**Figure 7a**) with an average of 594 mm (39% of annual rainfall). Soil moisture deficit in the area varies from 375 to 503 mm (**Figure 7b**) and higher values are found in the BT. The monthly water balance study reveals that water deficit starts in December and continues until May in the western part, while it starts in December and continues until April in the eastern part of the area.

4.2. Groundwater scenario

4.2.1. Trends in groundwater depth

Our previous studies [7, 9] evaluated the spatio-temporal scenario of groundwater level of the study area. To confirm about the trends obtained in the most recent (1991–2010) groundwater level, we have reanalyzed the long-term (1971–2011) data. The plots of long-term average groundwater level data of the study area, linear trend, and Sen's Slope have been shown in **Figure 8**. Similar to the results of recent period data [7, 9], statistically significant increasing trends have been found in 86.67% dry season long-term groundwater depths time series data. Moreover, trend analysis of wet season groundwater depth also shows almost similar result. Significant increasing trends in groundwater depth with high magnitude of changes are found in the BT. The

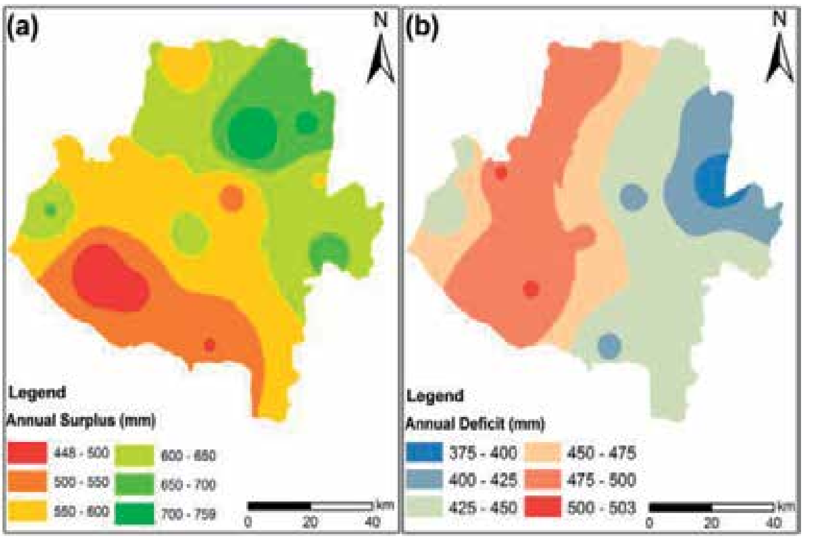

Figure 7. Annual surplus and deficit of water found from the water balance study over the study area.

increasing depth of groundwater during the wet season indicates that groundwater withdrawal of the area is unsustainable, and aquifers of the area are not fully recharging during the wet season. During the period of 1991–2010, on an average 9–14 m groundwater level depletion occurred in the area. People are not getting drinking water during the dry season using HTWs as the water runs far below the suction mode of the pump [7]. Farmers of the area have also mentioned that they are not getting water with a full swing from DTWs during the dry season.

4.2.2. *Groundwater recharge*

To calculate groundwater recharge of the study area, groundwater level data of 73 (**Figure 1**) monitoring wells for the period of 1991–2010 have been used. The average net groundwater recharge in the area varies from 153 mm in Patnitala to 580 mm in Godagari with an average of 325 mm. The previous study [33] showed that groundwater recharge ranges from 109 to 572 mm (**Figure 9**) with an average of 330 mm. There is no notable difference between the estimated average net groundwater recharge and previously estimated groundwater recharge [33]. However, there are notable variations in some Upazilas. Groundwater recharge in some Upazilas in the study area has been increased in comparison to the previous study.

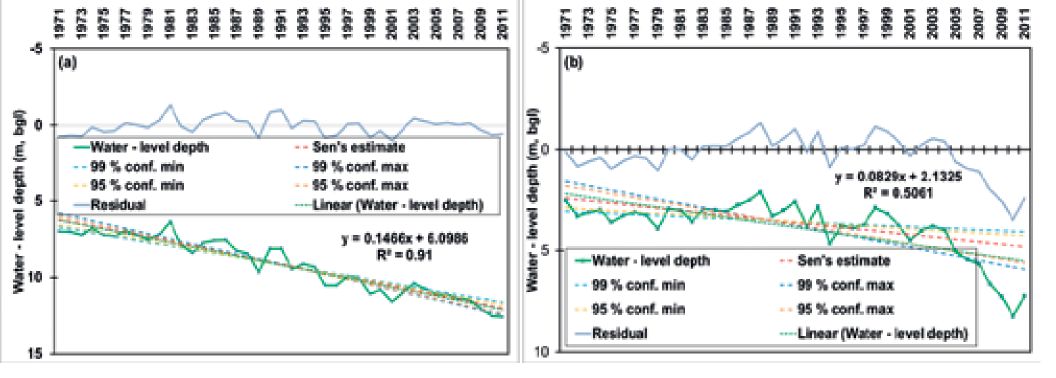

Figure 8. Linear trend in groundwater depth in the study area and Sen's slope at different confidence levels (a) dry season and (b) wet season.

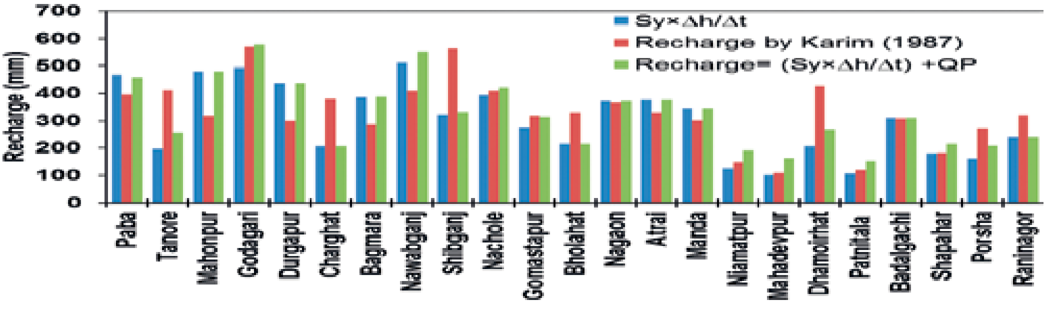

Figure 9. Upazila wise calculated values of $S_y \times \Delta h/\Delta t$ (mm), groundwater recharge (mm) calculated by Karim [33], values of groundwater recharge (mm) considering groundwater abstraction during rainy season.

The increasing amount of groundwater recharge may relate to the favorable recharge structures created by BMDA such as re-excavation of *Kharis*, rivers, etc. Groundwater recharge in some places of BT increases, but declining trends in wet-season groundwater level indicates recent groundwater storage depletion [23].

4.2.3. Driving forces of groundwater depletion

The areas irrigated by Shallow Tube Wells (STWs), DTWs, and Power Pumps (PPs) were 368, 180, and 81 thousand acres, respectively, in 1993, which increased to 978, 679, and 121 thousand acres, respectively, in 2010. The groundwater abstraction for irrigation in 1993–1994 pumping season was about 2543.3 million cubic meters (Mm^3) for greater Rajshahi district and it was 7195.3 Mm^3 in 2010. The groundwater abstraction for the irrigation pumping season 1993–1994 to 2009–2010 is shown in **Figure 10a**. The estimated Z (5.05) statistic indicates a statistically significant trend in groundwater abstraction at 99% confidence level. Hence, this significant trend is a significant responsible factor for groundwater depletion in the area. The Padma River, which is one the mighty river in Bangladesh, flows along the south of the study area. Aquifer feeds the river during the dry season (Nov–May) as the river water level goes below the groundwater level and river feeds the aquifer during the rainy season [34]. The trends in annual maximum and minimum discharge of the Padma River are shown in **Figure 10b**. It is seen that both the maximum and minimum discharge are decreasing over the years. However, the decreasing rate of minimum discharge (−132.45 m^3/s) is higher than that of maximum discharge (−22.27 m^3/s). This is one of the reasons for the rapidly increasing trend in groundwater depth during the dry season in the study area. The Padma river which originates in India is a transboundary river. India is controlling the flow of the river. Hence, transboundary river relation is also a driving factor of groundwater depletion in the study area. Moreover, decreasing rainfall and frequent droughts are also responsible factors for rapid depletion of groundwater level [7, 8]. Furthermore, the thick clay surface lithology (15–30 m) lies over the aquifer in the central part of the area is the inherent problem of groundwater recharge in the study area. It is also one of the driving forces of groundwater depletion.

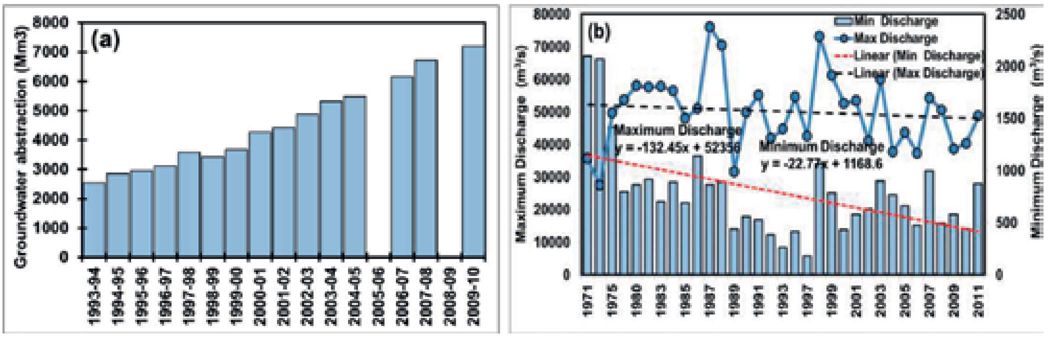

Figure 10. (a) Groundwater abstraction during 1993–1994 to 2009–2010, (b) annual minimum and maximum discharge of Padma river.

4.3. Alternatives for achieving sustainability in water resources management

4.3.1. Surface water potentiality

Surface water is the best alternatives of groundwater. BMDA [35] conducted a detailed survey on the surface water potentiality in the northwest Bangladesh. The survey data have been analyzed and presented in **Table 1**. There is a scope to irrigate 23,565 ha (hectares) of land using surface water from different sources in different Upazilas in the northwest Bangladesh. 9285 ha of land can be easily irrigated by surface water as the surface water always available over the years (A+). In addition, 4035 ha of land can be taken under surface water irrigation scheme by re-excavating the existing rivers and *Khals* in different Upazilas in northwest Bangladesh. Almost 5.08% of irrigated land can be irrigated from surface water sources (**Table 1**) in the northwest Bangladesh.

4.3.2. Managed aquifer recharge

MAR as a mechanism of storing water in underground is gaining popularity in the different parts of the world [36]. An experimental study on MAR in two villages (Mallickpur and Ganoir) in the study area has been done in Nachole Upazila in Chapai Nawabganj district (**Figure 1**). VES survey has been conducted in the selected sites to know the lithology and optimum depth of recharge wells. Two bore holes have been done to confirm about the interpreted lithology from VES and these bore holes later used as recharge well. The topmost layer (Zone-I) is characterized by clay lithology with thickness varies from 22 to 27.5 m. The resistivity value of Zone-1 ranges from 9 to 28 Ωm. There exists an aquifer (Zone-II) composed of fine to medium sand lithology with thickness varies from 8 to 20 m. The resistivity value of Zone–II ranges from 63 to 198 Ωm. This aquifer is treated as the main aquifer having potentiality for groundwater development for drinking purposes. The schematic diagram of MAR has been shown in **Figure 11**. Rainwater falls on the roof of the corrugated iron in household level. Rainwater is collected through a pipeline system and poured through into a storage system (**Figure 11**), which is a recharge box. The total catchment is used for rainwater harvesting is 200 m^2 with five recharge points in each village. Before injecting the rainwater through the recharge structure into the aquifer, it makes free from any sorts of silt and debris present. The recharge box (1.5 m × 1.5 m size) is filled with brick cheeps of 6, 10, and 20 mm sizes and coarse sands. The depth of the recharge box is 3 m in the top clay layer. The recharge well has been constructed at the bottom of the recharge box, so that water can enter in the recharge well after filtering in the recharge box. There is a strainer at the bottom of the recharge well where it meets the aquifer. Finally, the rainwater enters into the aquifer through the strainer. The groundwater level is monitored by observation wells in both villages. Rain-gauge stations have been set up to record it. Eighty percent of rainfall has been considered as effective rainfall for recharge as rainfall loss occurs during heavy rainfall events. To ensure the quality of groundwater, water quality of both sites has been analyzed before and after the implementation of MAR. The water is safe for drinking before and after the MAR [37]. The average maximum and minimum water-level depth was 14.6 (m, bgl) and 5.2 (m, bgl) during the period of 1991–1995 in Nachole Upazila, respectively. Average maximum and minimum water level

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Upazila	Upazila area (km^2)	Irrigated area (%) of total area	Irrigated area (ha)	Potential surface water irrigation areas (ha)					
				A+	A	B	C	Total	Irrigated area (%)
Bagha	184	27	4975	—	270	—	—	270	5
Bagmara	363	59	21,417	—	—	2210	—	2210	10
Charghat	165	71	11,715	200	300	450	—	950	8
Mohanpur	163	72	11,736	—	390	700	—	1090	9
Paba	280	71	19,880	300	300	400	—	1000	5
Puthia	193	90	17,370		120	810	—	930	5
Bholahat	124	90	11,117	250	—	175	110	535	5
Gomastapur	318	39	12,407	2200	550	—	—	2750	22
Nachole	284	36	10,212	575	—	—	—	575	6
Nawabganj	452	52	23,494	3440	—	—	—	3440	15
Shibganj	525	45	23,644	750	—	—	225	975	4
Atrai	284	76	21,584	470	690	—	—	1160	5
Badalgachi	214	72	15,408	—	—	200		200	1
Dhamoirhat	301	90	27,090	—	—	1000	120	1120	4
Mohadevpur	398	83	33,034	980	685	110		1775	5
Naogaon	276	93	25,668	—	—	250	210	460	2
Niamatpur	449	55	24,695	—	—	—	200	200	1
Patnitala	382	61	23,302	120	280	—	—	400	2
Porsha	253	41	10,373	—	—	690	600	1290	12
Raninagar	258	92	23,766	—	450	450	320	1220	5
Sapahar	245	37	9065	—	—	315	700	1015	11

Note: A+: Potential surface water sources located in dry areas and water is available over the years; A: Surface water is available in some years during dry season; if re-excavated, water will be available over the years; B: Surface water is not available during dry seasons; if re-excavated, water will be available over the years; and C: Surface water is not available; if re-excavated, it is possible to conserve water for irrigation purposes.

Table 1. Potential surface water irrigation areas in different Upazilas (sub-district) in northwest Bangladesh (data source: BMDA [35]).

went down to 18.9 (m, bgl) and 12.2 (m, bgl) during 2006–2010, respectively. The regaining of GWL during the rainy season were 9.4, 12.4, and 11.7 m during 1991–1995, 1996–2000, and 2000–2005, respectively. However, it was only 6.5 m during the period 2006–2010. The regaining of GWL in the area was the lowest during 2006–2010 due to inadequate recharge and heavy withdrawal of groundwater for supplementary irrigation during rainy season. Artificial recharge structures in the two villages in Nachole Upazila ware installed in the month of November in 2013. The water-level depths of both villages show the regaining of GWL in

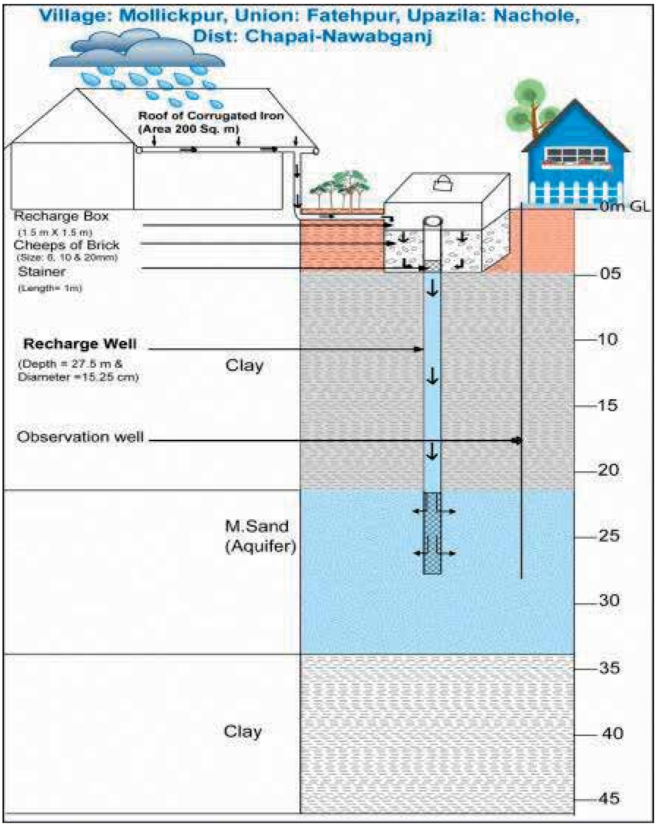

Figure 11. Schematic diagram of MAR technique implemented in Nachole Upazilla, Chapai Nawabganj district.

response to artificially augmented recharge over the last 2 years. The maximum water-level depth was 13.66 (m, bgl) in Mallickpur Village in May in 2014, but it was 09.88 (m, bgl) again in May in 2015. This result indicates that water-level depth was 3.78 m above than the previous year depth as the cumulative effective rainfall for the period of Jan–May was only 103 mm in 2014, but it was 448 mm in 2015 for the same period. The people of the area mentioned that they were not getting water using their HTWs during the months of Mar–May. However, now they are getting water using their HTWs during this period. Furthermore, in Ganoir Village the same kind of scenario has been observed and water-level depth was 1.47 m above in 2015 than in 2014. The amount of GWL restoration is not same for both villages. This difference is mainly due to the difference in rainfall and other factors like the elevation of the recharge point and rate of abstraction may also responsible.

5. Conclusions and recommendations

The compass of this chapter is to understand the long-term hydro-climatic characteristics and evaluate the performance of MAR for achieving the sustainability in groundwater

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management. Our intent was not to cover all the aspects related to the sustainability of water resources management. However, the findings of the study will contribute to understanding the phenomena related to sustainable groundwater management in drought prone areas. Our study demonstrates that unplanned irrigation for the dry season rice production is the significant responsible factor for groundwater depletion. Moreover, climate-related factors, like decreasing trend in rainfall, distribution of rainfall (SI and PCI), frequent drought, are also related to the groundwater depletion. In the study area, the thick clay surface lithology, which is the barrier of groundwater recharge, is also an important factor for groundwater depletion. The study also demonstrates that water resources management also related to the transboundary river relationship. To achieve sustainability in groundwater resource management particularly in the study area, water resource managers need to consider several factors along with the factors mentioned. First, it is time to take decision about the land use patterns as rice, which cultivates in about 81% cultivable area during the dry season, is the highest water consuming crop in the area. Though it is the staple food in the country, it is necessary to reduce this crop cultivation to protect rapid depletion of groundwater resource. Moreover, water-saving irrigation techniques such alternate drying and wetting, raised bed techniques need to promote for farming. Surface water irrigation where and when it is available need to facilitate to minimize the stress on groundwater. The present study also indicates that groundwater recharge in some Upazilas increases due to create favorable recharge structures like re-excavation of rivers and *Kharis* (small channel). However, the effort is not quite enough for protecting groundwater depletion. As annual surplus water is higher than the net groundwater recharge, groundwater recharge favorable structures for rainwater harvesting need to develop. An experimental study on MAR shows the potentiality of the technique for ensuring drinking water supply especially in the rural areas. An IWRMP considering the driving forces of groundwater depletion, potentiality of surface water, and MAR and land use pattern of the area need to prepare and execute the plan accordingly for achieving the sustainability in water resources management.

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Section 3

Transboundary Issues

Chapter 8

Transboundary Cooperation and Sustainable Development in the Rhine Basin

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Additional information is available at the end of the chapter

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Abstract

The Rhine connects millions of people from the Alps to the North Sea. With a length of 1233 km, its catchment includes nine states, an area of about 200,000 km^2, 60 million inhabitants as well as important cities and fascinating landscapes. Consequently, the Rhine is culturally, historically and economically one of the most important rivers in Europe. The International Commission for the Protection of the Rhine (ICPR) was founded in 1950 with the first common goal in history to reduce water pollution. The whole process got a new impetus with the chemical catastrophe at the Sandoz plant (near Basel) in 1986, which saw aquatic ecosystems being seriously damaged. This disaster led to a better integration of the issue of ecology into the tasks of the ICPR. Depollution and rehabilitation programmes with actions and measures were established. In the 1990s, severe flood events forced the ICPR to add flood prevention to its sustainability goals enabling a better protection of citizens. This chapter presents the common work of the countries aimed at protecting the Rhine basin and the most important environmental outcomes of this special and long-lasting partnership.

Keywords: Rhine, Rhine basin, integrated river basin management, transboundary cooperation, international water management, water quality, ecology, alluvial areas, biotope, ecological continuity, migratory fish, water quantity, flood risk management, low water, low flow, climate change

1. Introduction

The Rhine connects millions of people from the Alps to the North Sea. With a length of 1233 km, its catchment includes nine states, an area of about 200,000 km^2, 60 million inhabitants as well as important cities and fascinating landscapes (**Figure 1**). Consequently, the Rhine is culturally, historically and economically one of the most important rivers in Europe.

Figure 1. States in the Rhine catchment.

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The states and regions in the Rhine basin (Switzerland, France, Germany, Luxemburg, the Netherlands, Austria, Liechtenstein, Wallonia, Italy as well as the European Union) all join forces in the International Commission for the Protection of the Rhine (ICPR) founded in 1950 to improve the sustainable development of the river and its catchment [1]. The first historical common goal of the ICPR was to reduce water pollution. The whole process got a new impetus with the chemical catastrophe at the Sandoz plant (near Basel) in 1986, which saw aquatic ecosystems being seriously damaged. This disaster led to a better integration of the issue of ecology into the tasks of the ICPR. Depollution and rehabilitation programmes with actions and measures were established. In the 1990s severe flood events forced the ICPR to add flood prevention to its sustainability goals to enable a better protection of citizens.

This chapter presents the common work of the countries for the protection of the Rhine basin and the most important environmental outcomes of this special and long-lasting partnership.

2. Integrated Rhine river basin management: the ICPR

2.1. Historical background

For many centuries, the Rhine river has played an important role in the history and the social, political and economic development in Europe. Multiple uses, conflicting interests and particularly environmental and flood problems in and along the river have highlighted the importance of an integrated approach aimed at protecting the Rhine.

The foundation of the ICPR 5 years after the end of World War II was a first political success. On 11 July 1950, the ICPR began its discussions on issues of Rhine protection and monitoring with a view to finding joint solutions. Mutual confidence had to be carefully created in the international working groups of the ICPR. The high pollutant loads and the contamination of the Rhine with salt were of great concern for the downstream users.

Thirteen years after its foundation, the ICPR was given a status under international law. In 29 April 1963, the envoys of the German, French, Luxembourgian, Dutch and Swiss government signed the “Convention on the International Commission for the Protection of the Rhine against Pollution” in Berne [2]. One year later (1964), a permanent international secretariat was established in Koblenz, Germany, to coordinate the cooperation of the contracting parties in the working languages German and French, since 2003 also in Dutch.

2.2. A real step-by-step approach

At the beginning of the activities of the ICPR, between 1950 and 1970, the first challenge was to establish a common Rhine water quality monitoring from Switzerland down to the Netherlands. However, there was no improvement of water quality to measure. On the contrary, by the end of the 1960s, the Rhine water quality was worse than ever. In 1972, the ministers in charge of environmental protection in the Rhine catchment met for their First Conference of Rhine Ministers. In their next meeting in 1973 in Bonn, they charged the ICPR to draft a Chemical

Convention and a Chloride Convention [3]. Both Conventions were signed in 2 December 1976 in Bonn together with an additional protocol to the Berne Convention of 1963 which confirmed the European Economic Community becoming a contracting party to the ICPR.

In the 1970s and 1980s, successful programmes were developed to reduce inputs of polluted municipal and industrial wastewater, with the focus on "end-of-pipe" techniques, that is, wastewater treatment, rather than on preventive measures within the industrial enterprises. As a result of these measures, the concentrations of toxic substances also dropped.

The Sandoz accident in 1986 clearly illustrated the disastrous impact accidental pollution can have on the whole river. Due to a fire in a Swiss factory producing chemical and pharmaceutical products, between 10 and 30 tons of insecticides, fungicides and herbicides flushed into the river with the fire extinction water and killed almost all aquatic life between Basel and Koblenz (approx. 400 km downstream). Citizens from Switzerland downstream to the Netherlands demonstrated solidarity with the Rhine and its protection. The considerable public pressure exercised on the governments of the states in the Rhine catchment contributed to the increasing influence of the ICPR. The riparian states of the Rhine were forced to act. The governments—triggered by two Rhine ministerial meetings after the accident—charged the ICPR to draft a plan aimed at saving the river. One year later the Rhine Action Programme (RAP) was ready for approval [4]. It was designed to thoroughly rehabilitate the Rhine by the year 2000.

When adopting the RAP, the ministers agreed on very challenging and ambitious targets like the return of the salmon by the year 2000 and a 50–70% reduction of inputs of dangerous substances between 1985 and 1995. All along the river, measures were taken to prevent pollution (see Part 3). Since 1970, more than 80 billion Euros have been invested into constructing municipal and industrial wastewater treatment plants; today, about 96% of the population in the Rhine catchment are connected to municipal wastewater treatment plants.

Almost all reduction targets were achieved by 2000. Inputs of most priority substances were reduced by 70–100% or were no longer detectable. The success of the Salmon 2000 and Salmon 2020 programmes is evident [5]. Although completely extinct in the 1950s, by 2016, almost 8900 adult salmon returned to the Rhine basin for spawning (see Part 4.5). Further measures are required to achieve a self-sustaining salmon population in the Rhine catchment. The ongoing reactivation of parts of the former floodplain areas will lead to more room for the river, higher biodiversity and a more natural river system (see Parts 4 and 5).

The concept of further integration of policies received an extra impetus and stronger political commitment after the extreme floods in 1993 and 1995 (see Part 5). Two floods were needed to convince the Rhine states that flood prevention measures had to be taken. In 1998, the ICPR adopted an Action Plan on Floods [6]. By 2010, important action targets were achieved after implementing different measures entailing costs of 10.3 billion Euros [7]. With the aim of reducing extreme flood levels, retention areas for 229 million m^3 of flood water along the main stream have been created.

Since 1998 and in order to integrate the main uses and functions within the Rhine basin in the working process, the ICPR grants an observer status to non-governmental organisations (NGO) and stakeholders, thus giving them the possibility to participate in the plenary assemblies and in working expert groups [2]. The observer status offers public participation to a certain extent and enables information dissemination to a larger public. Further ways of informing the general and specialised public are the website of the ICPR (www.iksr.org), various brochures, reports and workshops.

In addition, the cultural importance of the Rhine river must be highlighted. Landscapes, many old Roman towns as well as preserved floodplains and lakes are attracting tourism and leisure activities. Many examples prove that sustainable recreational uses of the Rhine and its environment are possible. The Upper Middle Rhine Valley between Bingen and Koblenz is classified as UNESCO World Heritage Site, and therefore there is an obligation to find the right balance between landscape conservation and tourism development.

To sum up, integrated river basin management was developed within the ICPR step-by-step: the ICPR has been dealing with the reduction of water pollution since 1950, with ecosystem improvement since 1987, with water quantity issues since 1995 and with groundwater issues since 1999. Now, all topics are integrated into the two European Directives (Water Framework Directive (WFD) 2000, several daughter directives and the Floods Directive (FD) 2007), and the ICPR is coordinating the basin-wide implementation of both directives within the international river basin district Rhine (IRBD Rhine) [8, 9]. The special ICPR programme is called "Rhine 2020 – Programme on the sustainable development of the Rhine" [10].

3. Water quality improvement and challenges

As mentioned in Part 2, water quality improvement has been a main ICPR task since the Commission's establishment in 1950. The Rhine has had to face tremendous pollution. Flowing through densely populated and industrialised areas, it had to cope with huge loads of untreated wastewater in the past. Additionally, there was some accidental pollution as, for example, the severe Sandoz accident in 1986.

Between 1950 and 1970, the ICPR established a uniform monitoring programme from Switzerland down to the Netherlands (**Figure 2**). This required a comparison of the different national monitoring stations and an agreement on an international monitoring programme, the substances to monitor, monitoring frequency, sampling dates and analytic methods. Due to a joint approach of the authorities in charge, the Rhine water quality could and can still be assessed reliably and on a scientific basis.

During the last 40 years and following the many measures taken, the water quality of the Rhine and of many of its tributaries has considerably improved. At an early stage, in the beginning of the 1980s, the ICPR recommended its member states to include a third treatment stage (elimination of phosphates) when planning new wastewater treatment plants. One of the results of this recommendation is that the Rhine water quality steadily improved, in particular with respect to heavy metals, total phosphorus and ammonium nitrogen (**Figure 3**).

The improved water quality is also reflected by the development of oxygen concentrations at the monitoring stations Rekingen (High Rhine, Switzerland), Koblenz (Middle Rhine,

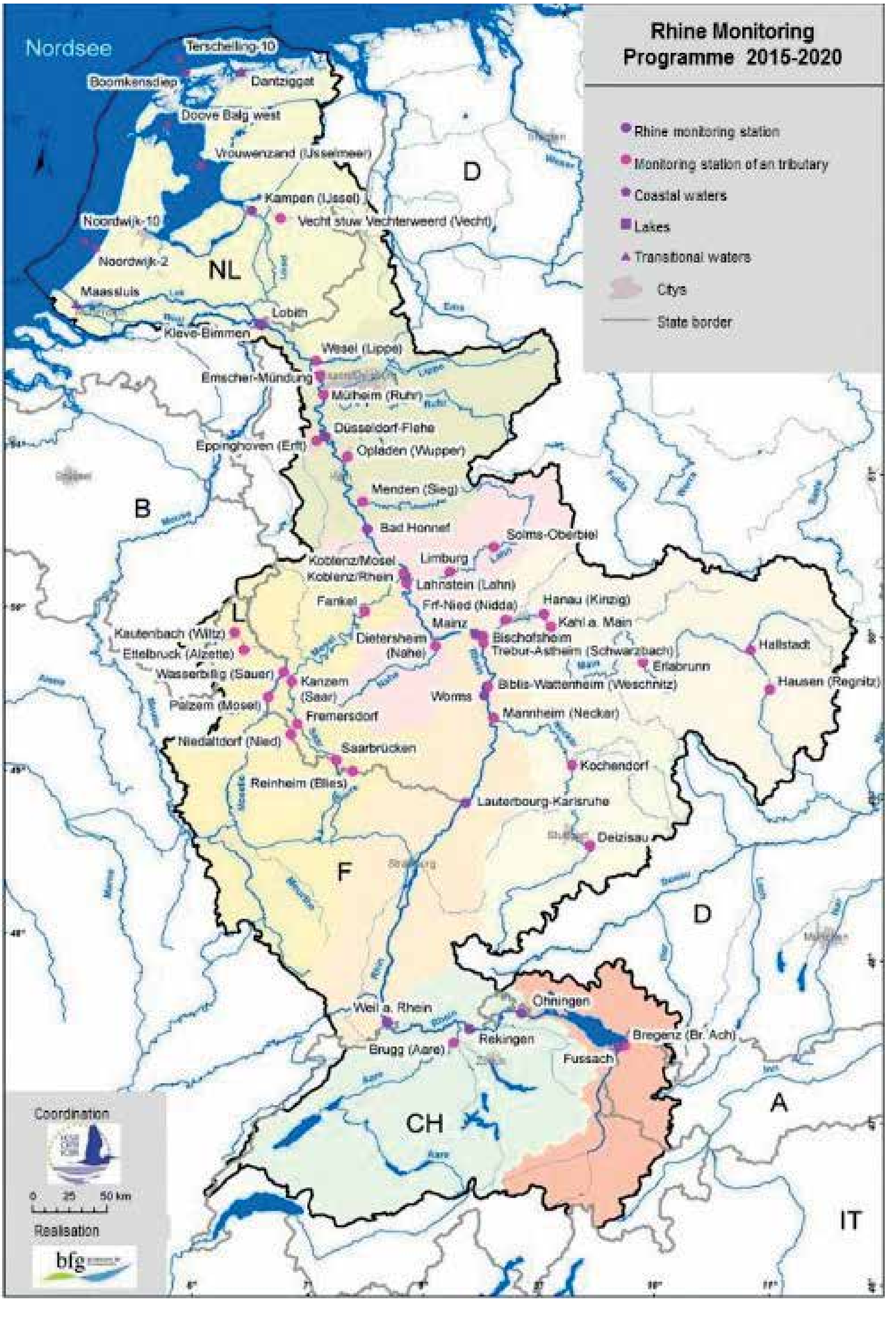

Figure 2. Monitoring stations of the Rhine monitoring programme (2015–2020) [11].

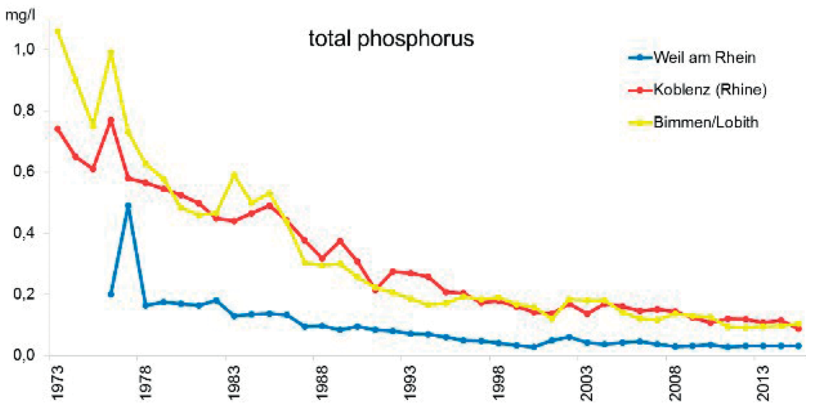

Figure 3. Annual average concentrations of total phosphorus from 1973 to 2015 in Weil am Rhein (near Basel), Koblenz (Middle Rhine) and Bimmen/Lobith (German-Dutch border).

Germany) and Bimmen/Lobith (Lower Rhine, German-Dutch border) between 1954 and 2015 (**Figure 4**).

The political approaches were changed to a long-term ambitious goal setting, and programmes combatting pollution and furthering river restoration were launched shortly after the Sandoz accident. Within short time, three conferences of ministers were staged [12], leading to the adoption of the RAP in 1987 (see Part 2).

After the accident at Sandoz in 1986, the ICPR also improved its international Warning and Alarm Plan (WAP) [13]. If, in spite of all preventive measures, an accident occurs or great amounts of hazardous substances flow into the Rhine, the WAP is activated, which above all

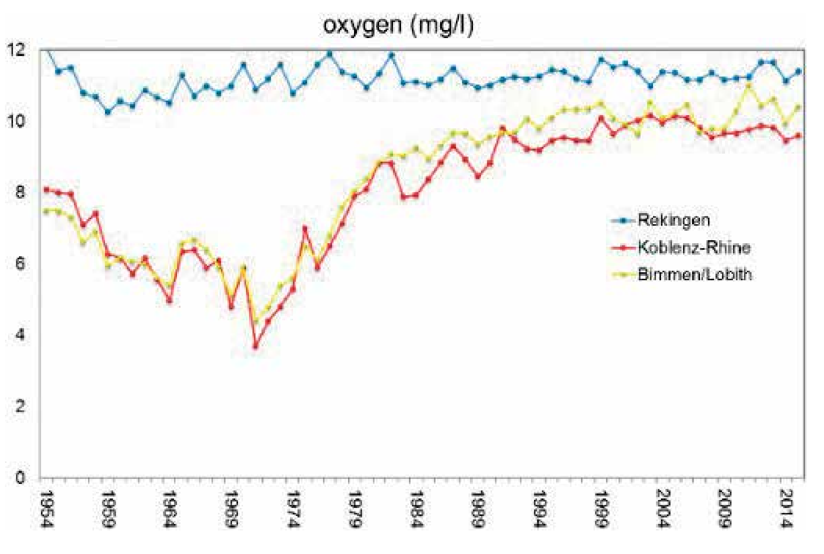

Figure 4. Annual average concentrations of oxygen from 1954 to 2015 in Rekingen, Koblenz and Bimmen/Lobith.

warns all users downstream (**Figure 5**). Apart from warnings, which are only issued during huge and serious water pollution events, the WAP is more and more also used as an instrument for exchanging reliable information on sudden water pollution measured by monitoring stations along the Rhine rivers, Neckar and Main and smaller tributaries.

Another consequence of the Rhine Action Programme was that requirements concerning municipal and industrial wastewater treatment plants became distinctly stricter.

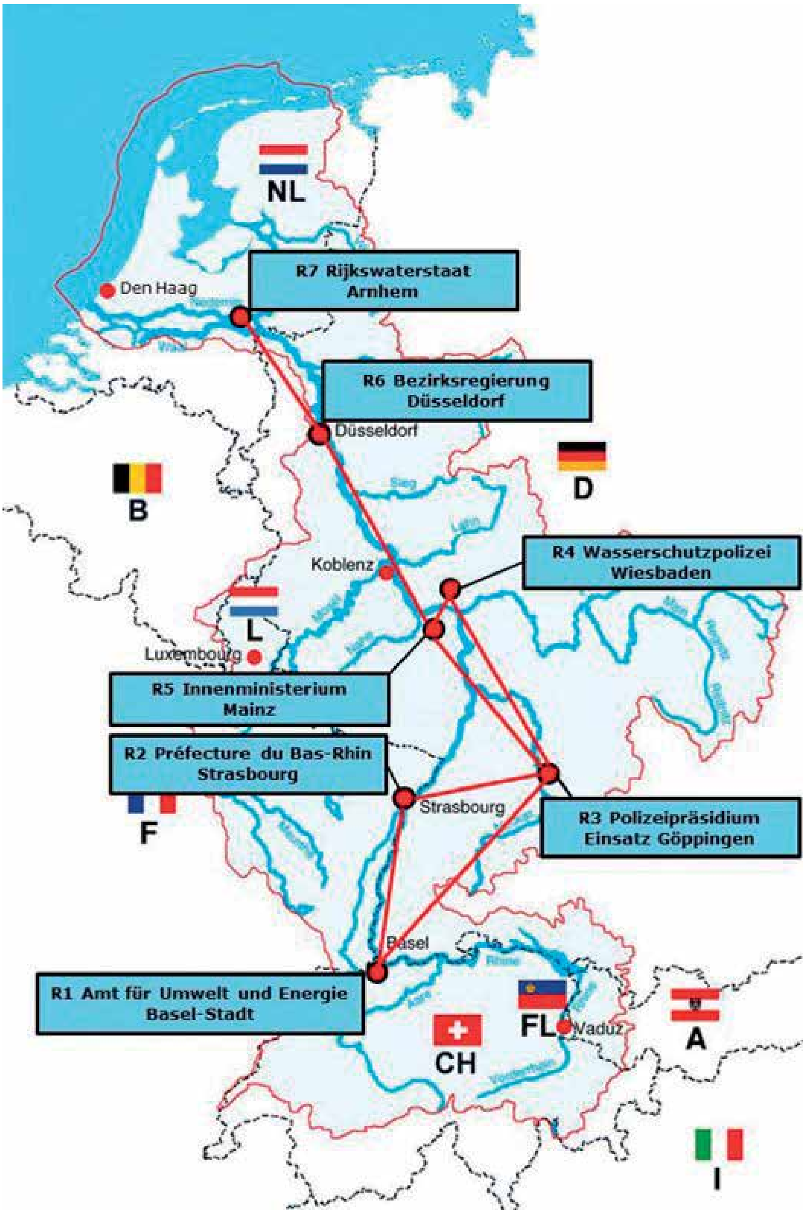

Figure 5. The international main alert centres and the exchange of information.

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Following this most successful Rhine Action Programme, the ministers in charge of the Rhine adopted "Rhine 2020" [10]. In this new programme, the ICPR recommended goals regarding the water quality for environmental quality standards; the phased reduction of emissions; the guarantee to produce drinking water using simple and near to nature treatment procedures; the further reduction of the accumulation of hazardous substances in organisms; the uncritical consumption of fish, mussels and crustaceans; the disposal of dredged material, bathing and the depollution of the North Sea.

The pollution of the Rhine with heavy metals and other pollutants has been reduced (**Figure 6**). Additionally, the amount of polluted Rhine sludge has decreased. For instance, the quantity of polluted harbour sludge that the city of Rotterdam had to dispose sunk from 10 million cubic metres in 1987 to about 1 million cubic metres per year in 2016.

Today, water bodies in the Rhine watershed are used for many, partly concurrent purposes which almost always modify water bodies and impact on water quality. In order to reach a sustainable situation, uses and protection of the Rhine and its tributaries must be brought into an acceptable balance.

Worldwide, the Rhine figures among the most important shipping lanes and is the most important one in Europe. Compared to other means of transportation, inland navigation is rather environmentally friendly. Nevertheless, it still directly and indirectly contributes to deteriorating the ecological state and water quality of the Rhine. The ICPR and the Central Commission for the Navigation of the Rhine (CCNR) are closely cooperating on different environmental issues. Examples of actions helping to achieve environmental objectives are information and recording losses of pollutants from navigation and the "Convention on the collection, deposit and reception of waste produced during navigation on the Rhine and inland waterways" (CDNI).

The impact of the different uses is regularly monitored within international and national monitoring programmes, in order to be able to assess the impact of their stress. The results

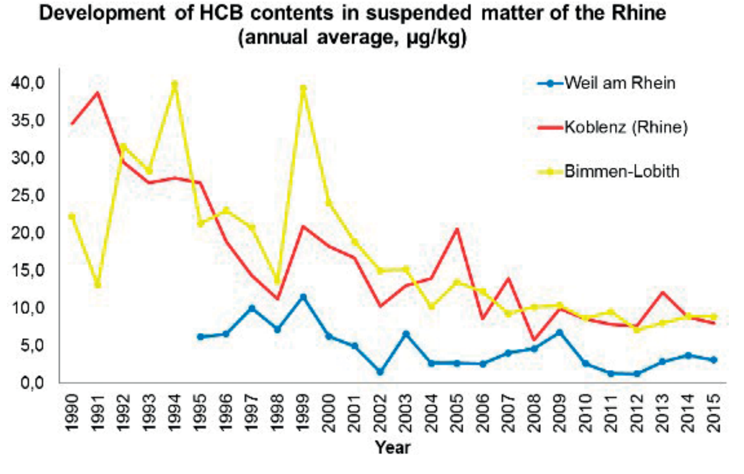

Figure 6. Annual average concentrations of HCB (hexachlorobenzene) in suspended matter from 1990 to 2015 in Weil am Rhein (yellow), Koblenz (red) and Bimmen/Lobith (purple).

and an assessment of the water quality are summarised and published by the ICPR, from 1956 to 1999 as books and since 2000 on the Internet [14]. In addition to the regular monitoring programmes, the ICPR established a platform for new and upcoming techniques. Since 2015, laboratories in the Rhine catchment using nontarget analysis meet on a regular basis in an expert group. In 2017, the ICPR organised a special monitoring programme including nontarget analysis. This will help to get a better overview over potential pollutants in the Rhine and its tributaries.

In spite of improvements in water quality, a few substances are still detected in too high concentrations. This particularly concerns ubiquitous substances (e.g. mercury), which are persistent and occur almost everywhere in the Rhine catchment [15]. Unfortunately, there are few measures capable of reducing the pollution with these substances on the short run.

Additionally, micro-pollutants are of concern for water quality. There is a diverse group of micro-pollutants, like medicinal products (e.g. carbamazepine) (**Figure 7**) or odoriferous substances, which are partly not eliminated in the wastewater treatment plants. Very low quantities of these pollutants are detectable in waters and may detrimentally affect life in the Rhine and drinking water production.

The active pharmaceutical agents of medicinal products are detected in the Rhine catchment area. The highest concentrations are measured in the Lower Rhine and in tributaries with a high share of municipal wastewater. Wastewater treatment plants have been identified to be a main pathway of input for all therapeutic products for human use and their transformation products. One example of an active pharmaceutical agent in the Rhine catchment area is carbamazepine which is used for the treatment of seizure disorders and neuropathic pain (**Figure 7**).

The Conference of Rhine Ministers (2007) [12] assigned the ICPR to develop a joint and comprehensive strategy for reducing and avoiding micro-pollutant inputs from urban wastewater and diffuse sources into the Rhine and its tributaries by improving knowledge on

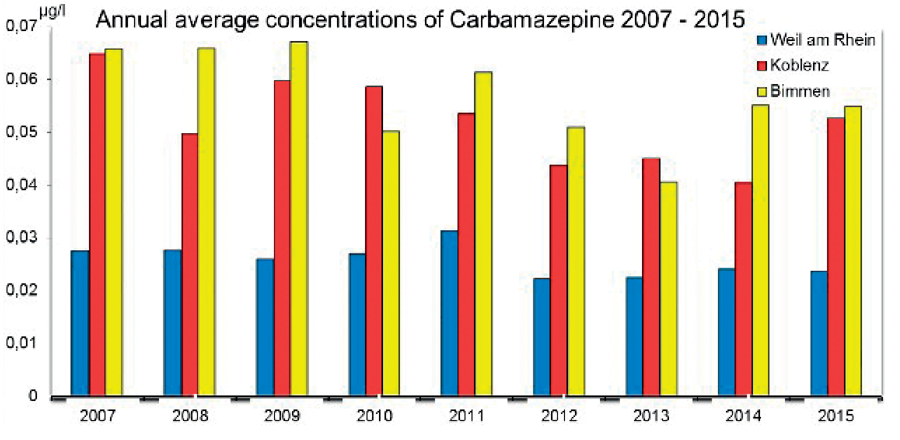

Figure 7. Annual average concentrations of carbamazepine from 2007 to 2015 in Weil am Rhein, Koblenz and Bimmen.

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emissions and ecotoxicological reactions in nature and to draft suitable treatment methods. The knowledge collected since 2008 has been published in several ICPR reports [16, 17].

The ICPR will continue its efforts towards reducing point source inputs, inputs of diffuse origin (e.g. nutrients and plant protection agents) and the inputs of micro-pollutants.

Although we are still facing challenges to improve the water quality, the Rhine, one of the largest rivers in Europe, has undergone an impressive restoration. The ICPR programmes are a success story, as pollution could be reduced so that the salmon is coming back to the Rhine (see Part 4).

4. Conservation and rehabilitation of aquatic ecosystems

4.1. Ecological balance and ICPR programme “Rhine 2020”

Due to the cooperation of the Rhine-bordering countries within the ICPR, not only the water quality of the Rhine but also its ecological state has further improved. Many intermediate aims for the ecological revalorisation of the Rhine river stated in the “Programme for the Sustainable Development of the Rhine – Rhine 2020” have already been achieved [7, 10, 18]. Besides, the common implementation of the Internationally Coordinated Management Plan 2015 for the IRBD Rhine is currently going on [15].

Alluvial plains of the Rhine are again flooded, oxbow lakes are reconnected to the river and along short stretches the river structures have been ecologically improved. The number of animal and plant species has increased. Since 2006, salmon and other migratory fish may again reach Strasbourg on their way upstream from the North Sea (**Figure 8**).

The connection of the different habitats along the Rhine from Lake Constance to the sea in order to achieve habitat patch connectivity is successful. In this connection, the ICPR sets definite targets and spatial focal points aimed at linking water protection with nature and

Figure 8. Atlantic salmon (source: Ulrich Haufe, AugenBlick Naturfilm).

flood protection. In spite of the success achieved, the ecological functionality of the comprehensive Rhine system is not yet satisfactory.

Above all, the ecological continuity of the Rhine from Lake Constance to the sea and of its tributaries must be further improved. Further targets are to increase the structural diversity of the banks of the Rhine and its arms and the extension of alluvial areas [7, 10]. With a view to restoring the ecological continuity of the Rhine and its tributaries, the ICPR has drafted a "Master Plan Migratory Fish Rhine" [19].

4.2. Fauna and flora

Many hundreds of animal and plant species live in the innumerable different habitats along the Rhine and its tributaries (**Figure 8**). The presence of a particular species permits conclusions regarding the ecological state of the habitat. Therefore, some fish typical of a specific habitat and other water organisms serve as indicators for the ecological state. Plankton and water fowl also play an important role.

The ICPR regularly publishes summary reports on all biological analysis results of the 6-year monitoring cycle [18]. The last biological inventories showed that with a number of 64 species in the Rhine, the range of fish species is almost complete again [18]. Apart from fish, the Rhine fauna consists of worms, mussels, snails, crustaceans, insects, birds and mammals. From the Alpine Rhine until the North Sea, more than 500 invertebrate species—called macrozoobenthos—were detected on the bed of the Rhine. Many water plant species have also returned to the Rhine. Thus, the ecological network is in a distinctly better state than in the 1980s.

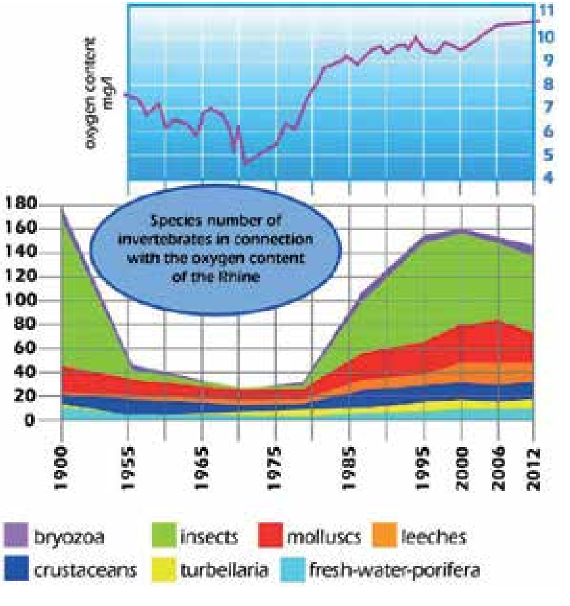

Figure 9. Development of the invertebrate communities of the Rhine and average oxygen content of the Rhine at Emmerich (Lower Rhine).

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This result was achieved by improved wastewater treatment (as mentioned in Part 3) and more river continuity. **Figure 9** shows the development of the average oxygen content and of the invertebrate communities in the Rhine at the German-Dutch border.

However, today's biological diversity in the Rhine is different from that in former times, as many new species have settled, which will remain part of the future water system. Measures aimed at restoring waters and removing obstacles to migration will favour indigenous species and strengthen the ecosystem.

4.3. Alluvial areas

Alluvial areas are essential for the Rhine ecosystem as they represent valuable nature resources and act as natural flood buffers. They increase water retention and are thus important means of flood prevention (see also Part 5). Reactivating floodplains along the Rhine and reconnecting alluvial waters are two important measures aimed at ecologically upgrading the Rhine [18]. Such ecological support is required, as numerous river training measures along the Rhine and almost all tributaries have basically modified the hydrological and morphological conditions. For example, cutting off more than 85% of the alluvial areas along the Upper and Lower Rhine has led to great losses of habitats and of animal and plant species typical for the Rhine.

The ICPR programme "Rhine 2020" for a sustainable development of the Rhine includes targets to reactivate 160 km^2 of floodplain along the Rhine and in the lowlands of the Rhine

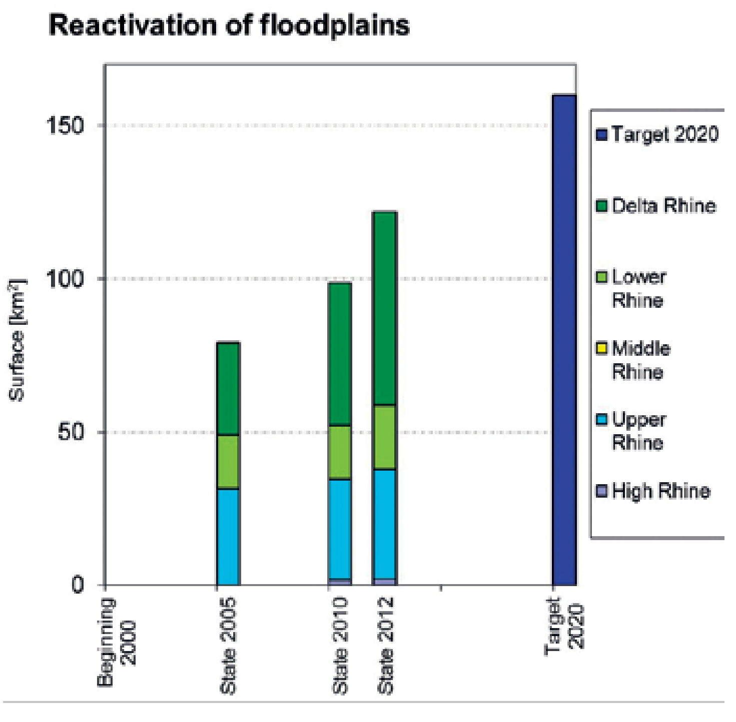

Figure 10. Reactivation of floodplains between 2000 and 2012.

and 1000 km^2 in the entire Rhine watershed as well as to renature 11,000 km of flowing waters by 2020. Furthermore, 100 old water courses of the Rhine and backwaters are to be reconnected by 2020. A first balance revealed that the intermediate targets set for 2005 had been achieved and that progress continues. By 2012, about 122 km^2 of alluvial areas along the Rhine had been reactivated and 80 old water courses of the Rhine and backwaters had been reconnected (**Figure 10**) [7, 10, 18].

4.4. Habitat patch connectivity

In order to maintain an ecological continuity, biotopes along the Rhine must again be interconnected. Once the connected habitats of the Rhine and its tributaries present an ecological continuity, animals may move up- and downstream (see also Section 4.5 on migratory fish), and plants may be carried away by the currents. After eventual extreme situations, such as floods and low water periods, they may recolonise up- or downstream sections from lateral waters. Therefore, habitat patch connectivity is a very important functional characteristic of the Rhine ecosystem which will serve water protection, nature protection as well as flood protection. The sum of all measures will also support the increase of biodiversity in the ecosystems of the Rhine. For these reasons the re-establishment of the habitat patch connectivity along the Rhine from Lake Constance to the North Sea is one of the targets set by "Rhine 2020" and is also part of the report and the atlas of the ICPR for achieving a habitat patch connectivity along the Rhine [20–22].

4.5. Importance of ecological continuity for migratory fish

Restoring the ecological continuity of the Rhine from Lake Constance to the North Sea and that of priority tributaries for recolonisation is also a distinct target of the ICPR "Master Plan Migratory Fish Rhine" [19]. The Master Plan is supposed to indicate how self-sustaining, stable migratory fish populations can again be settled in the Rhine watershed as far as the Basel area within both reasonable time and at reasonable costs.

During their life cycle, anadromous long-distance migratory fish like salmon (spawning in fresh water) and the catadromous eel (spawning in marine waters) migrate from the sea into fresh water or from fresh water into the sea for the purpose of reproduction (**Figure 11**).

Formerly, the Rhine catchment used to be an important habitat for migratory fish. However, since the nineteenth century, systematic river training, e.g. for navigation and hydropower uses, on the Upper and High Rhine and along many tributaries has heavily interfered with ecological continuity in the Rhine system (see Part 4.3). Transverse structures, such as weirs or barrages, may seriously interfere with or completely obstruct migration in a water body. Spawning grounds and juvenile fish habitats of migratory fish have partly been destroyed and are no longer accessible, or their accessibility is considerably reduced.

Due to the implementation of the Master Plan Migratory Fish Rhine, ecological continuity has been improved at more than hundreds of barrages, e.g. by constructing fish passes (**Figure 12**), and in 2015, 21% of the salmon spawning grounds were again accessible. Since about the year 2000, annually several hundreds of salmon again migrate upstream to the Upper Rhine and reproduce naturally in the accessible salmon waters [23].

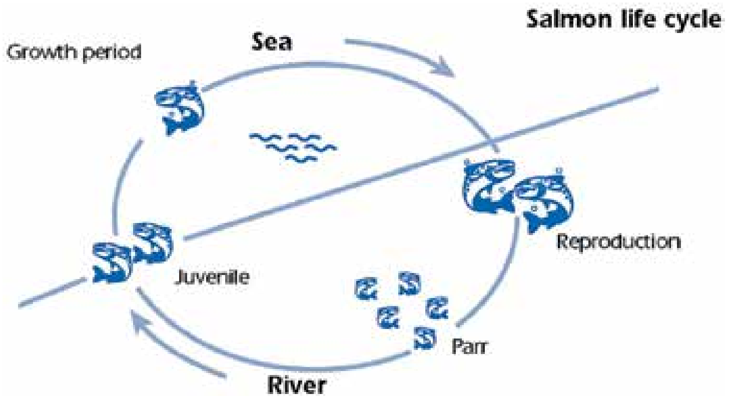

Figure 11. Life cycle of migratory fish Atlantic salmon.

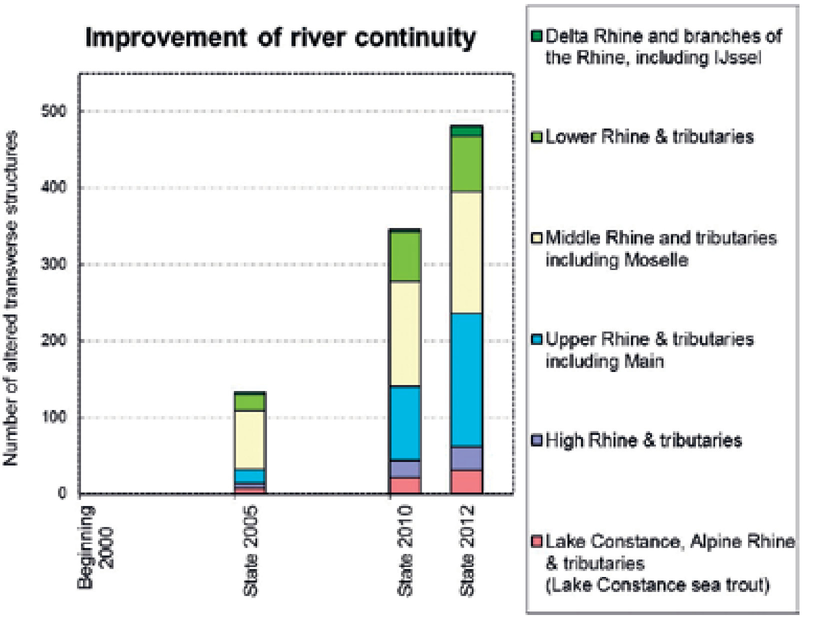

Figure 12. Improvement of river continuity between 2000 and 2012.

5. Reducing the impacts of water quantity issues (floods, low flows)

The topography of the Rhine catchment varies and includes different climatic zones (alpine, low mountainous, Atlantic, semi-continental climate). Different discharge regimes are overlapping: a “snow regime” in the southern part near the Alps with flood events mainly occurring in summer (snow melt) and low water periods mainly in winter. Waters draining the Central Upland region (Neckar, Main, Nahe, Lahn, Moselle, etc.) are characterised by a “pluvial regime” with prevailing winter floods and low flows in summer. Since these two regimes overlap, the downstream discharge distribution over the year is uniform ("combined regime") [24, 25].

Furthermore, climate change consequences for the discharge lead to more homogenous runoff in the south, while the seasonal distribution becomes more marked in the north. These tendencies continue during the twenty-first century, and, due to reduced runoff in summer, they might even be intensified (**Figure 13**) [25, 26]. Together with land settlement and man-made water works, this is already now resulting in diverse flood and low flow patterns.

As stated in Part 2, the two catastrophic flood events on the Rhine in 1993 and 1995, causing, respectively, 1.4 and 2.6 billion euros damages, were the starting point for the ICPR to deal with quantitative issues and flood risk (**Figure 14**) [6, 7]. Because of several low flow events since the 2000s and their negative impacts, the Rhine Ministers decided in 2013 to address this issue and undertake an in-depth analysis of low flows and their consequences (**Figure 15**) [12]. Apart from that, the ICPR is working on the topic of climate change effects on the water regime and the water quality and environment (**Figure 13**). Since 2015, the ICPR has published a first Climate Change Adaptation Strategy for the Rhine Basin based on hydro-climatic observations and measurements from the twentieth century and scenarios for the twenty-first century [25, 27]. The different working groups of the ICPR (dealing with water quality, ecology, flood and low water) have made a thematic assessment of the respective consequences and proposed actions which have been integrated into the strategy.

The focus in this subchapter will be on flood risk management, as low water has just begun to be treated within the ICPR. Interesting results about low water change, repercussions, etc. will be available in the upcoming years.

5.1. Transboundary flood risk management

Since 1998, the ICPR has implemented the Action Plan on Floods [6, 7] which set out four action targets: reduce damage, water levels, improve flood forecast and risk awareness. Since 2007 it has established a framework for the exchange of information and coordinated implementation of the European Floods Directive (FD) within the IRBD Rhine [28].

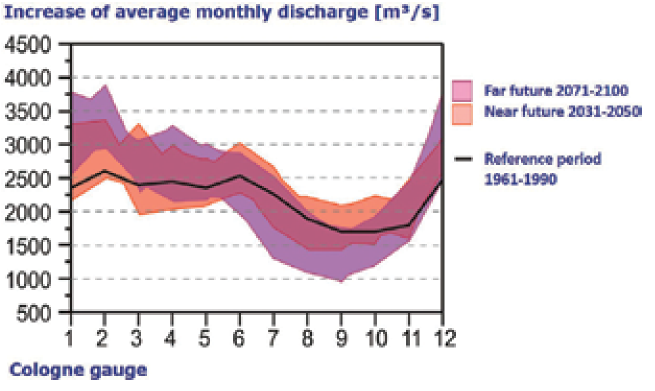

Figure 13. Possible effects of climate change on discharges in the near and far future (Cologne).

Figure 14. 1995 Flood in Cologne, Germany (source: Stadtentwässerungsbetriebe Köln).

Figure 15. 2015 Low water in Koblenz, Germany.

The objectives of the FD concern the management of flood risk in order to reduce potential adverse consequences of floods for human health, the environment, cultural heritage and economic activities. The Directive stipulates extensive cooperation in the field of flood management in international river basin districts. Based on the principle of solidarity, the states should avoid taking measures which, due to their extent and their effect, increase the flood risk in other countries upstream or downstream in the same river catchment as long as these measures are not coordinated between the member states concerned and no common solution has been found.

In accordance with the FD, different common products (reports, maps) have been drafted and published on the ICPR homepage, among others, the first overriding Flood Risk Management Plan (FRMP) (2016–2021) for the Rhine basin (see measures of the FRMP in Part 5.1.2) [28]. The measures of the FRMP Rhine are currently being implemented by the states themselves, and discussions have started to prepare the second FRMP (2022–2027).

5.1.1. Principles and targets of the FRMP

Consistent with the APF [6] and the FD, the Rhine states have determined common principles for the FRMP:

- Responsibility, solidarity, proportionality and clear task distribution (between the states when it comes to flood risk management).
- Synergy with other EU environmental politics (specially the WFD; see Parts 3 and 4).
- Sustainable and integral flood risk management.
- The security level has to be ecologically, economically and socially compliant.
- No 100% security, always residual risks.

These principles are translated into four overriding, general targets representing the whole flood risk management cycle (prevention, protection, preparedness, crisis management and recovery) (**Figure 16**). Relying on these targets, the states have decided joint measures presented in Section 5.1.2.

5.1.2. Presentation of joint measures of the FRMP

The FRMP for the Rhine basin describes measures with transboundary effects and measures, for which an exchange of information and an international coordination between the states in the Rhine catchment are important. The FRMP Rhine also includes information and links to the national and regional FRMPs.

5.1.2.1. International coordination of measures

The EU member states in the Rhine catchment are in charge of implementing the FD and apply the principles of subsidiarity and solidarity. In order to respect these provisions, the states, Länder and regions within the IRBD Rhine have agreed not to increase flood risks outside their respective territories. To this end, they will effectively coordinate measures with transboundary

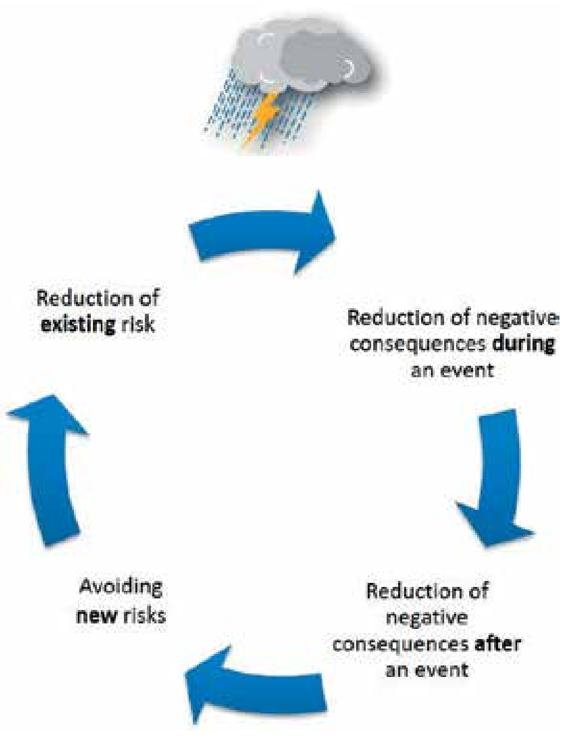

Figure 16. Overarching targets and simplified risk management cycle.

effects. Furthermore, according to the WFD and FD, some measures, e.g. retention areas, have to be coordinated or present synergies between the goals of the FD and the WFD.

5.1.2.2. Implementation of measures aimed at lowering the water levels

As stated in the Conference of Rhine Ministers (2013), and due to the effects of climate change and the expected increase of the number of flood events, supra-regional flood risk management measures such as keeping flood-prone areas free from further uses or creating more flood retention areas and more room for the river are increasingly important. Therefore, the Ministers decided the further and consequent implementation of all measures aimed at lowering water levels or of retention measures along the Rhine planned until 2020 within the framework of the APF (**Figure 17**).

The following measures aiming at lowering water levels are related to the latter and are included in the FRMP (**Figure 17**): future retention areas, dike relocation, renaturing (**Figure 10**) and keeping discharge corridors free (see Part 4). For the further measures, the securing of the surfaces under aspects of spatial planning is being determined in the FRMP.

According to an ICPR study [7, 29], a reduction of flood peaks will be achieved once all planned measures will have been implemented (**Figure 18**). The results permit a substantiated evaluation of the effectiveness of measures implemented and of their contribution to achieving the objectives of the FRMP.

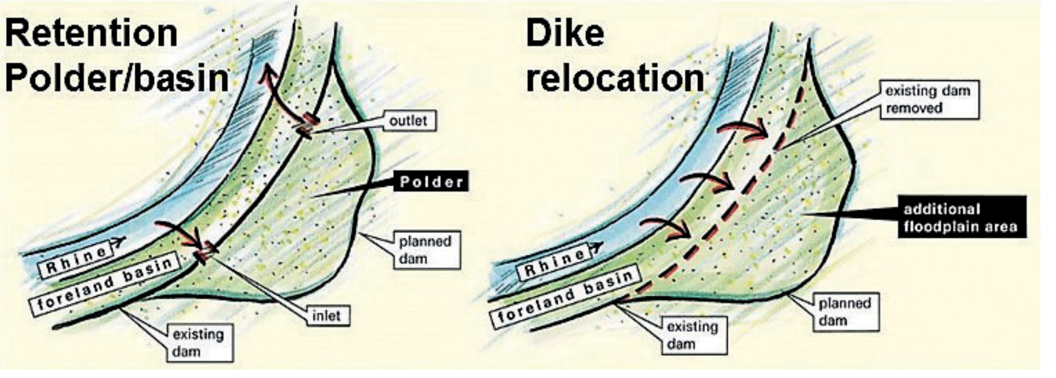

Figure 17. Example of measures aimed at lowering water levels: retention basin and dike relocation (source: Regierungspräsidium Freiburg—Integrated Rhine Programme (2011)).

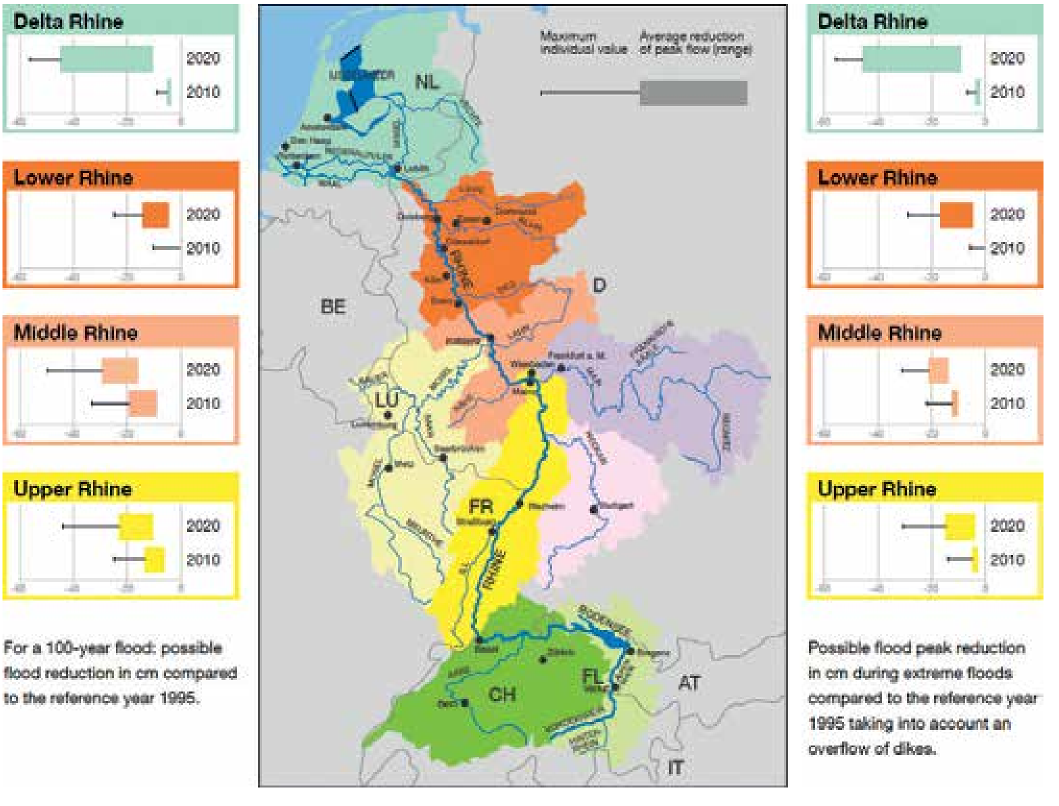

Figure 18. Possible reduction of flood peaks due to measures lowering the water level (State 2010 and 2020).

The reduction of water levels by different corresponding measures along the Rhine (**Figure 18**) may equally lead to reduced flood probability [29, 30]. This also results in a reduction of flood risks. The results of this study [30] were used for calculating the modification of flood risk with the GIS instrument [31, 32].

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5.1.2.3. Improved exchange of information and access to information

The mutual exchange of information on flood risk management is done at the ICPR level. The population is also being well informed on a national, regional or local scale, so that regional specifics may be taken into account. The "Rhine Atlas" [33] is a supranational sensitisation tool comprising aggregated flood hazard and risk maps (**Figure 19**). For the main stream of the Rhine, flood depth and areas as well as objects at risk are shown for three scenarios (high, medium and low flood probability). Additional information and more detailed national maps are available by clicking on any area of the atlas. Together with uses adapted to floods, it also supports the implementation of preventive measures in flood-prone areas.

5.1.2.4. Instrument for the assessment of the impact of flood risk management measures on risk evolution

The ICPR, supported by the engineering consultant HKV, developed the instrument "ICPR FloRiAn (Flood Risk Analysis)" aimed at evaluating the effect of measures to reduce flood risk and at estimating the future evolution of flood risk. The instrument, working in a consistent, reproducible and transparent manner, is available on demand at the ICPR and is applicable to other river basins [31, 32]. ICPR FloRiAn is GIS based and in the case of the ICPR covers the main stream of the Rhine. Flood maps (e.g. developed under the FD) are the basis for the tool. In addition to the quantification of economic flood risk, modules are developed for quantifying the consequences of risk for human health, to the environment and to culture heritage. In short, the main instrument consists of three interacting calculation modules (Model Builders) resulting in an overall damage or risk assessment.

The ICPR uses this tool to assess risk reduction and evolution along the Rhine from 1995 up to now as well as to carry out regular reviews of the impacts of measures on flood risk reduction for the FRMP. Calculations made with the help of ICPR FloRiAn proved—among other results—the reduction of flood risks by 25% between 1995 and 2020 for economic activities. Under a supra-regional aspect, measures increasing water retention in the direct vicinity of the Rhine river prove to be most efficient (**Figures 17** and **18**) [31, 32].

Figure 19. Rhine Atlas (flood hazard and flood risk maps).

5.1.2.5. Improve flood forecasting and warning systems as well as crisis management

Flood forecasting and flood announcement contribute to reducing damage in case of a flood event [7, 31, 32]. Therefore, the states, Länder and regions in the IRBD Rhine—through national centres along the Rhine (**Figure 20**)—cooperate at an international level when exchanging data

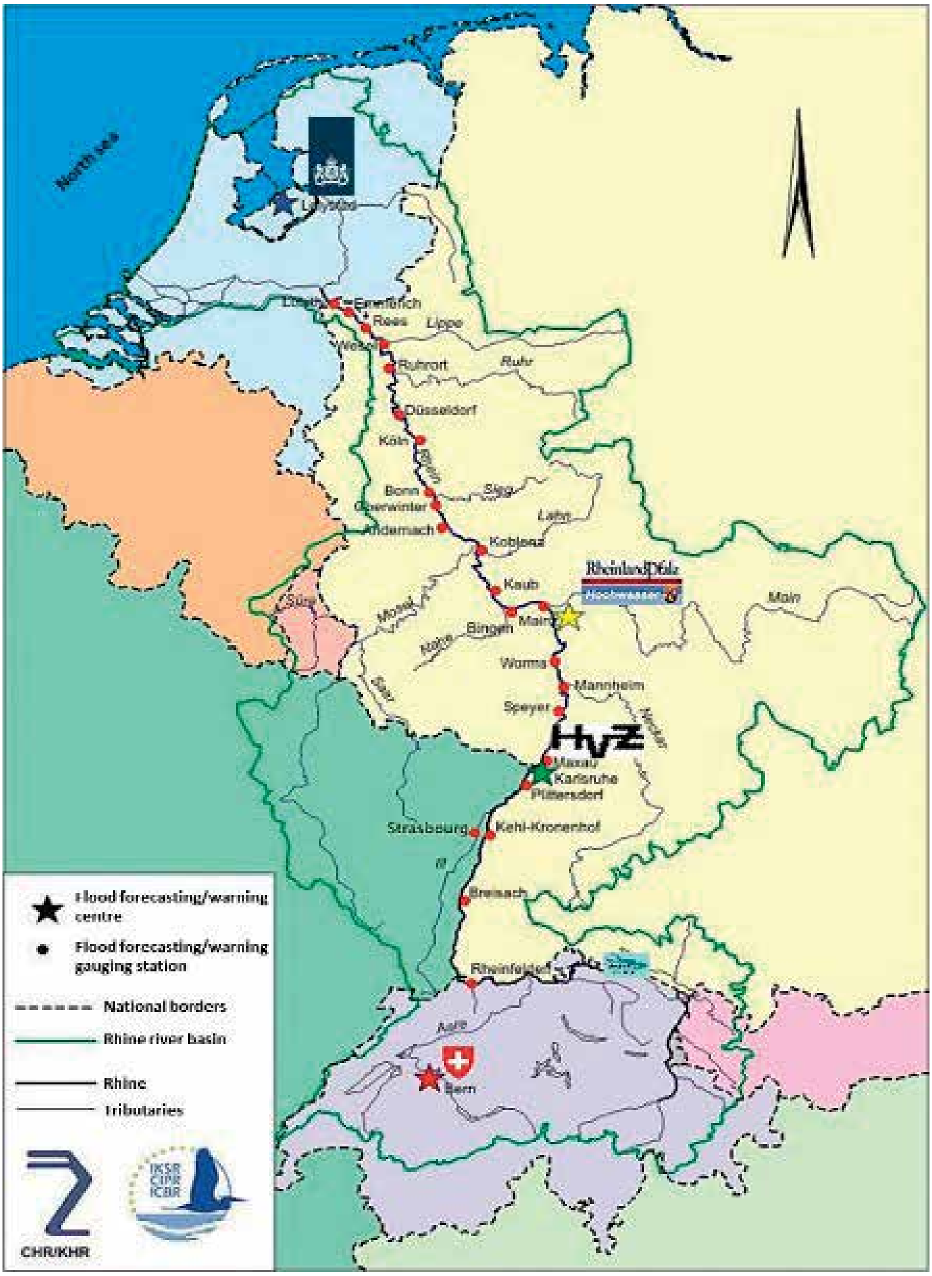

Figure 20. Flood forecasting centres along the Rhine.

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on discharge and precipitation and using them for flood forecasting [34]. The quality of information and forecasting is continuously being improved. Today, national mobile applications like "Meine Pegel" or "KATWARN" disseminate information and warn on water levels or storms (**Figure 21**) [35, 36].

Good crisis management planning for flood events is important in order to be able to reduce risks during the event. The ICPR has begun to compile existing multilateral crisis management systems and the understanding of national disaster risk reduction. If necessary, this exchange of information will enable improvements in this domain. This also applies to recovery measures.

5.2. The issue of low flows

Just as floods, low flows are natural, evident events that cannot be avoided. However, low water may considerably restrict navigation on the Rhine. The performance of hydropower plants may equally be reduced in times of low discharge. Besides, low flows can go hand in hand with high temperatures, leading to reduced oxygen content which may detrimentally impact the ecosystem. The Rhine states are therefore paying increased attention to the topic of low flows. In 2017, the ICPR (Expert group "Low water") has begun to analyse the trend of low water since the beginning of the twentieth century, to examine past low flow events and classify them in return periods. The ICPR is investigating the various consequences of low water for different uses of the Rhine. It is furthermore working on the inventory of national low water management measures as well as on low water monitoring.

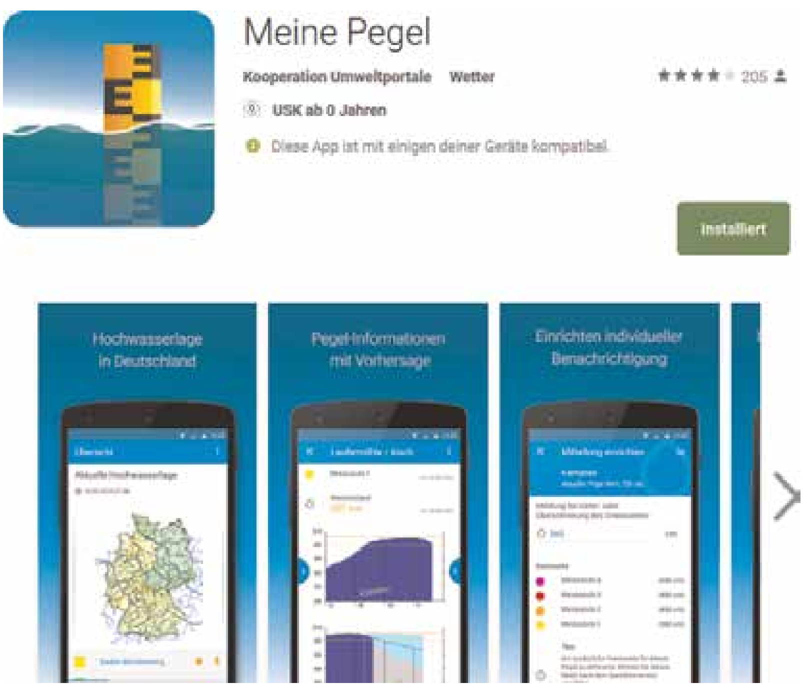

Figure 21. Mobile application "Meine Pegel" [35].

6. Conclusion

From being the sewer of Europe in the 1960s and 1970s, the Rhine has now become one of the cleanest international rivers in Europe. The Rhine and its densely populated catchment area have experienced heavy pollution and impressive restauration.

What started with the development of a joint monitoring strategy in the 1950s and 1960s has developed into a comprehensive integrated management strategy of the Rhine, comprising aspects of water quality, emission reduction, ecological restoration and flood prevention.

This development was guided by a process of "learning by doing" which was triggered by some major disasters (Sandoz accident 1986, floods in 1993 and 1995). These disasters have dramatically changed the political will in all states in the Rhine watershed. Public pressure after the disasters has been key to find common solutions towards restoring the Rhine river.

Since the beginning of the 1990s, the work of the ICPR has triggered the integrated water policy in the European Union. Today, basin-wide and transboundary approaches in water management and the required cooperation between all countries in a catchment are a European obligation.

The functions of the Rhine river, drinking water, water for agriculture and industries, water transportation, water power plants, recreational fishery, recreation and tourism, must be harmonised with ecosystem protection. The ICPR can look back upon a long tradition of cooperating with stakeholders like nature protection and different user associations.

This good transboundary cooperation was based on political willingness and the conscience of common interest, developed on strong pressure from public participation, good multilevel governance, the respect and solidarity of the countries within the basin and a high-level permanent secretariat.

Strong international coordination and cross-border cooperation have set the basis for the future development of the Rhine catchment and its related socio-economic and climate change challenges.

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Chapter 9

Monitoring of Meteorological, Hydrological Conditions and Water Quality of the Main Tributaries of the Transboundary Amu Darya River

Parviz I. Normatov and Inom Sh. Normatov

Additional information is available at the end of the chapter

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Abstract

The results of monitoring of meteorological, hydrological parameters and hydrochemistry of the main tributaries of the transboundary Amu Darya River, the Vakhsh, Zeravshan and Pyanj rivers are presented. The influence of climate change on the meteorological characteristics of river basins has been observed. The need for coordination of Central Asian countries in the implementation of integrated water resources management is suggested. It is pointed out that the lack of a developed network of hydrometeorological observation points and a low level of information exchange among the countries of the region often leads to the emergence of scientifically unjustified scenarios and forecasts of climatic and hydrological processes in the region. The creation of a single regional center for cryosphere and hydrometeorological observations for continuous monitoring of processes occurring with water objects in the region is proposed.

Keywords: transboundary, Central Asia, Amu Darya, Zeravshan River, Vakhsh River, isotope hydrology

1. Introduction

Water resources in the Aral Sea Basin, whose territory belongs to five states, are mostly used for irrigation and hydropower engineering. These water users require river runoff to be regulated with different regimes. The aim of the hydropower engineering is the largest power production and, accordingly, the utilization of the major portion of rivers annual runoff in winter, the coldest season of the year. Irrigation requires the largest water volume to be available in the summer, during the vegetation period. River runoff regulation is exercised by large reservoirs which, along with hydropower stations, are operated as part of complex purpose hydroschemes. The largest hydropower stations have been constructed in the republics of the runoff formation zone in the upper reaches of the Amu Darya and Syr Darya rivers—in Kyrgyzstan and Tajikistan, while the major land areas to be irrigated are concentrated in the republics in the lower reaches of the rivers—Kazakhstan, Turkmenistan, and Uzbekistan. The problems of water resources use and the appropriate river runoff regulation were solved in the USSR by administrative command methods based on nationwide interests [1]. The situation has radically changed after the collapse of the Soviet Union and the formation of five independent states in Central Asia. The conflict of interests between hydropower engineering and irrigated farming has become evident and acquired transnational significance. What are the causes of the present-day conflict between irrigation and power engineering in the region? The first cause is the excessive development of irrigated farming in the region in the 1960s–1990s, resulting in a strict demand for practically complete regulation of river runoff, both seasonal and over-years, and its complete consumption for irrigated farming [2, 3].

There is no doubt that the main water arteries of Central Asia (CA)—the Amu Darya and Syr Darya—are important in the life of the regional population, in the survivability components of the biosphere and are a key factor in the development of two important areas—hydropower and agriculture. The diversity values of rivers' water flow have specific requirements for finding a balanced mechanism for their use excluding drain pollution and ecological imbalance. Such a multifunctional approach to sustainable use and protection of water resources is achieved by the implementation of integrated water resources management.

Transboundary water arteries make special demands for expansion and joint efforts for the development of regional standards and norms for the use of water resources, as enshrined in interstate agreements. Implementation of the interstate agreements aspects on various points of joint use of water resources is largely determined by the level of observation, measurement of meteorological, hydrological parameters, water quality and condition of water bodies and the efficiency of their use.

The Amu Darya is a Transboundary river of Central Asia and flows through four countries (Afghanistan, Tajikistan, Uzbekistan, and Turkmenistan) and is characterized by a length of 2400 km, the basin area of 534,739 km^2. The main tributaries to the Amu Darya are Vakhsh, Pyanj and Zeravshan rivers.

In the 1990s, the area of irrigated land in the region rose to 9.0 million hectares. A sharp increase was observed in the energy sector. The total installed capacity of all power plants in the region reached by the mid-1990s of the twentieth century to 40 million kWt. Unfortunately, all these impressive results led to the same great negative consequences. The intensity of the disturbance processes of ecological balance in the region has sharply increased, especially in the Aral Sea and the Aral Sea zone, the salinization of lands and their desertification have increased and the quality of water has worsened in almost all sources. At the same time, by the 1970s, the water resources of the Syr Darya River Basin were almost completely depleted. This led to the frequency of water deficit, for example, in 2010, the water deficit in the region was 21.3 km^3/year and turned into a global environmental problem in the region [4, 5]. The second cause is the severance of economic ties between Central Asian countries after the collapse of

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the Soviet Union. In the Soviet period, irrigated farming was a priority in the use of water resources. At the same time, the hydropower engineering that was operated in the regime was unfavorable for the national interests of the countries in the upper reaches of the rivers.

What are the ways to resolve this problem? Paradoxically as it may be, a radical solution of the conflict between irrigation and hydropower engineering will be their joint rapid development with the construction of new large HPPs with large-volume reservoirs, rather than the restriction or subordination of one of them. In the case of hydropower engineering, this implies the production of economic and clean power. As for irrigation, this implies an increase in the depth of long-term regulation of runoff and water availability for the areas already developed, as well as the potential for the development of new areas. The availability of several hydropower stations with reservoirs will allow the contradictions between hydropower engineering and irrigation to be resolved. Nowadays, the conflict between them arises because there is only one large hydropower facility with a reservoir in the basin of each of the major rivers in the region: the Toktogul HPP in Kyrgyzstan on the Syr Darya and the Nurek HPP in Tajikistan on the Vakhsh River. A single large hydroelectric complex on a river cannot exercise runoff regulation in two regimes simultaneously—irrigation and power ones. The construction of one large hydroelectric complex on each of the two rivers will radically change the situation. In this case, the upstream reservoir will operate in a purely power regime, while the downstream reservoir with the same volume will be able to re-regulate the runoff and even restore its natural regime. Moreover, it will be able to ensure runoff regulation in the interests of irrigation. The availability of more than two hydroelectric complexes with reservoirs will allow the situation to be improved even farther.

Water relations between Central Asia republics during the Soviet Union time were regulated by "Complex Use and Protection of Water Resources Schemes" in Amu Darya and Syr Darya Basins.

The main purpose of working out basin "Schemes" was to define real volumes situated within the Amu Darya and Syr Darya basins and available water resources for using. It also provided their fair allocation among region republics, meeting all the water users' interests. It should be noticed that a number of important aspects were not considered and included in "Schemes," for the situation has greatly changed after 1980 (years of the last "Schemes" specification and completion of hydraulic range composition). Mainly, it concerns the ecologic acquirements and sanitarian clears thrown into rivers and channels. Overusing basin water in irrigational lands planned as maximum use by "Scheme" resulted in exhausting water resources and new problems: (1) deterioration of ecological condition, sometimes leading to ecological disaster in river lowlands of Aral Basin, (2) great pollution of river water with pesticides, herbicides, other harmful elements and increase of water mineralization [1].

The Zeravshan River is one of the transboundary tributaries of the Amu Darya River that is formed in Tajikistan and that flows into Uzbekistan. The average flow of the Zeravshan River is about 5.0 km^3 with an average annual flow of 158 m^3/sec [6, 7, 8].

The meteorological and hydrological monitoring of the Zeravshan River Basin conditions in the territory of the Republic of Tajikistan is conducted at four meteorological stations and the Dupuly hydrological station. The total area of the glaciers in the Zeravshan River Basin is 437.9 km^2. The Zeravshan glacier is the largest among the 632 glaciers with a length of 27.8 km and an area of

132.6 km^2. According to the Agency of Hydrometeorology of the Republic of Tajikistan, there have been significant changes of geometric dimensions and mass loss of Zeravshan glacier during the period 1927–1991. The glacier retreated 88–94 m/year for the period 1991–2001 and its area decreased by 700,000 m^2 and it is expected to decrease by 30–35% by 2050 [6, 9]. The next section provides an analysis of the Zeravshan River Basin meteorological condition.

The problem of the water quality change and development of mechanisms of its control is still actual and concerns not only the separately taken country of Central Asia (CA) but also all the states of the region. Nowadays one of the most polluted rivers of Central Asia is Zeravshan River. The capacity of this water is changed under the influence of collector drainage water of irrigating basin zone and wastewater of Samarqand, Kattakurgan, Navoi, and Bukhara cities. Mineralization of water exceeds from origin to estuary: from 0.27–0.30 to 1.5–1.6 g/l. The most exceed of maximum permissible concentration (MPC) among heavy metals is observed in Cr and Zn. Moreover, in Zeravshan River high amounts of antimony was found and its phenol pollution composes 3–7.5 MPC [1]. The problem of water quality in transboundary river basins, in particular in the Zeravshan River Basin, is compounded by the fact that up to now there is no network sharing of information regarding the quality of the waterways between the neighboring states of Central Asia. Herewith, a uniform standard for assessing of the anthropogenic load degree on geoenvironmental systems (maximum permissible concentration) is not developed. The problem of water quality of the Zeravshan River is mostly associated with its pollution by wastewater of the Anzob mountain-concentrating combine—the mining enterprise for extraction and enrichment of mercury-antimony ores of the Dzidzikurut deposit [10–18].

The Vakhsh River is the main river of the Republic of Tajikistan and one of the tributaries of the Transboundary Amu Darya River in Central Asia. It has a length of 691 km and the area of the basin is 39,160 km^2. The Vakhsh River originates when the Surkhob and Obikhingou Rivers merge at a height of 1151 m. The right inflow to the Vakhsh Rivers, the Surkhob River has a length of 81 km, and the basin covers an area of 1760 km^2 at an average altitude of 3140 m. There are 246 glaciers in the Sorbog River Basin covering a total area of 105.6 km^2. The left component of the Vakhsh, the Obikhingou River, is 196 km long by basin area of 6660 km^2 [6].

The Pyanj River is one of the tributaries of the Transboundary Amu Darya River in Central Asia by a length of 921 km and a basin area of 114,000 km^2. The average value of the water flow is about 1032 m^3/s. The total area of glaciation of the Pyanj River Basin is 3767 km^2 [19].

It is quite natural that the formation of the basic characteristics and the water quality of the main river runoff is the result of the imprint of the properties and parameters of its tributaries with prehistory meteorological conditions and the condition of its feeding sources (ice, snow-ice, rain, etc.). Therefore, the monitoring of hydrological characteristics, the study of the chemical composition of the main rivers tributaries and thus the creation of a database on the river basin meteorological conditions, hydrological parameters and degree of contamination are the pledge for preparation of the reliable information about the main river.

This chapter presents the results of many years' studies of the hydrological parameters, hydrochemical and meteorological conditions of the basins of the Vakhsh, Zeravshan and Pyanj rivers—the main tributaries of the Amu Darya.

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2. Objects and methodology

The object of study is the Vakhsh River and its tributaries—Surkhob and Obikhingou—by use of water discharge data corresponding to rivers from Hydroposts: on the Surkhob-Garm Hydropost; Obikhingou river—Tavildara-Yozgand; on the Vakhsh river—Darband for the period 1960–2012. For estimation of the meteorological conditions of the Kyzilsu, Obikhingou and Vakhsh rivers Basin, the meteorological data of the Lyakhsh, Tavildara and Garm meteorological stations were used.

The differential integral curves of average annual discharge are used to identify periods with high and low water run-off. The differential integral curve takes into account the fluctuations of the flow over relatively short periods. It is defined by summing the deviations of modular coefficients from the middle, that is, the ordinates are calculated as Σ (K−1). Thus, the ordinates of the curve at the end the cumulative sum of the annual modular coefficients gives the deviations from the long-term average (K = 1). The use of differential integral curves gives a vision of cyclical fluctuations without the effect of the boundaries displacement between the phases of the low and high duration cycles [6].

The Dehavz station meteorological data for the period 1931–2011 were used as it is close to the Zeravshan glacier and Iskanderkul in the Yagnob River Basin. Water flow of the Zeravshan

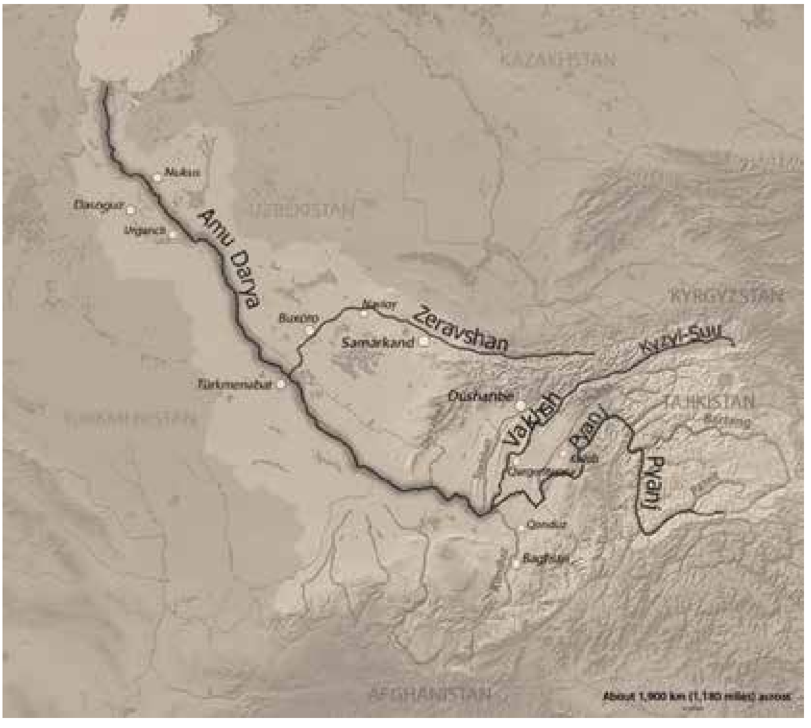

Figure 1. Amu Darya River Basin [32].

River was measured at the Dupuly Hydropost, which is the only operating station on the Zeravshan River. To determine the mean annual value of the water flow of the Zeravshan and Yagnob Rivers for the period 1931–2011, the data of the Agency for Hydrometeorology of the Republic of Tajikistan were used. Sampling of water from the Zeravshan and Vakhsh rivers and its tributaries were used by the scheme (**Figures 14** and **19**) developed in [11, 20] accordingly. The complex chemical water analyses were carried out by methods described in [9]. Sampling of water for isotopic analysis was carried out according to the methodology developed at the University of Colorado at Boulder (USA). Isotopic analysis of water was performed on Wavelength-Scanned Cavity Ringdown Spectroscopy (WS-CRDS). The individuality of each river from the point of view of chemical composition of water is compiled by sampling of the tributaries to the confluence with the main river and with other tributaries [20] (**Figure 1**).

The analysis of the meteorological conditions of the Pyanj River Basin and the dynamic change in temperature and precipitation were carried out using the date of the Agency of Hydrometeorology of the Republic of Tajikistan from the next meteorological station of the basin: Darvaz, Khorog, Dzavshangoz, Murgab and Gorbunov.

3. Meteorological and hydrological aspects

The meteorological and hydrological observations, the study of the glaciers state and the measurement of snow cover parameters are relevant at the upper reaches of Transboundary Rivers. Collection and systematization of such data is a source of forecasting the water flow of the corresponding rivers. Scientifically based and promising scheme of the main water consumer development—agriculture in the lower reaches of Transboundary Rivers is entirely determined from the degree of reliability and availability of a database on the values of the total water flow. The existence and continuous functioning of a developed network of observational and measuring stations on the watershed of the rivers is necessary in order to ensure uninterrupted and reliable information on meteorological and hydrological parameters. Taking into account the mountain orography of the Central Asian water resources formation zone, full-fledged climatic information can be provided only by a dense network of observations.

Unfortunately, the current situation of the hydrometeorological information exchange between the relevant agencies of Central Asian countries does not meet modern requirements. A low level of the information interchange causes the use of incorrect data and the emergence of a scenario of climate processes far from the real picture. Moreover, they become subject to mutual distrust and sometimes the appearance of conflict situations. It is clear that the implementation of uninterrupted hydrometeorological observations and the study of the state of water bodies located in hard-to-reach mountain areas are associated with the mobilization of huge material, financial and human resources. This plan requires a joint effort of the countries in the organization of a developed monitoring network with the extensive use of automatic stations and remote sensing methods. Of course, the existence and functioning of the regional center is necessary to coordinate the work of separate structures for integrated monitoring in the countries of Central Asia.

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3.1. Vakhsh River Basin

The location of hydrological stations of the Vakhsh River Basin shown in **Figure 2**.

The increase in the volume of river flows of the Vakhsh River and its tributaries, Surkhob and Obikhingou rivers (**Figure 3**), shows that currently there is a reduction of the Tajikistan glaciations areas resulting in increased snow melt, probably due to the overall temperature increase in the region and changing precipitation patterns [6].

In the Surkhob River Basin, there are intensively melting small glaciers of the Northern slopes in the Western part of a ridge of Peter the Great. On the southern slopes of the Alay Ridge, glaciation decreases slowly as there are larger glaciers. In the Obikhingou River Basin, the largest glacier Garmo is intensively melting. During the twentieth century, it became shorter by almost 7 km, having lost more than 6.0 km^2 in area. It is currently retreating at an average speed of 9 m/year and the surface settles up to 4 m/year due to melting. Another glacier in the same basin, Skogach, retreats at a rate of 11 m annually.

Another important aspect of the hydrology of the rivers, the cyclical nature of the water flow, should also be considered. Assessing the long-term fluctuations of annual runoff and their periodicity is important. On the other hand, there are attempts to link fluctuations in water availability with various geophysical processes. The lack of a clear periodicity in long-term fluctuation of flow does not rule out the tendency to have continuously alternating high water years, called cyclical fluctuations of water flow. The length of these cycles, their sequence and

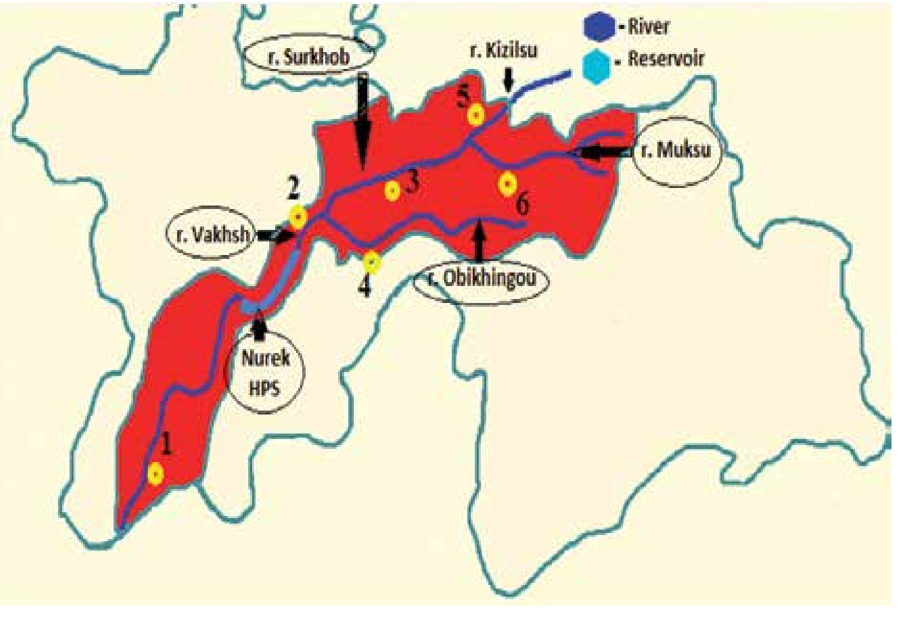

Figure 2. Vakhsh River Basin with location of hydrological stations: 1-Tiger Beam (R. Vakhsh), 2-Darband (R. Vakhsh), 3-Garm (R. Surkhob), 4-Tavildara (R. Obikhingou), 5-Dombrachi (Kizilsu), 6-Davsear (Muksu) [6].

the degree of deviation varies over a period. It is not always possible to make clear boundaries between wet and dry periods. Cyclical changes of the Vakhsh River runoff for the period 1932–2012 are shown in **Figure 4a** [6].

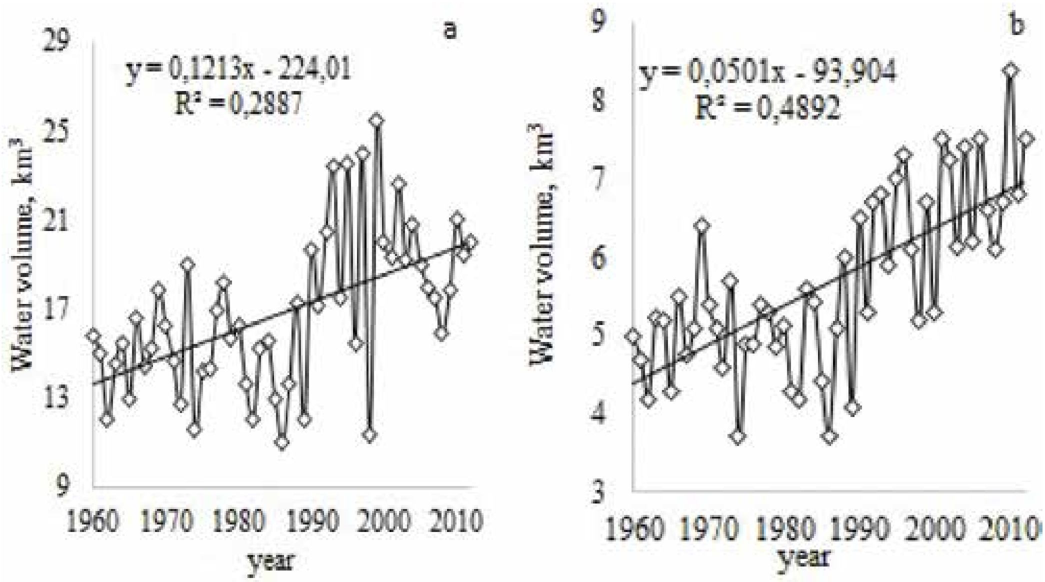

Figure 3. The water volume change of the Surkhob (a) Obikhingou (b) rivers for the period 1960–2012 [6].

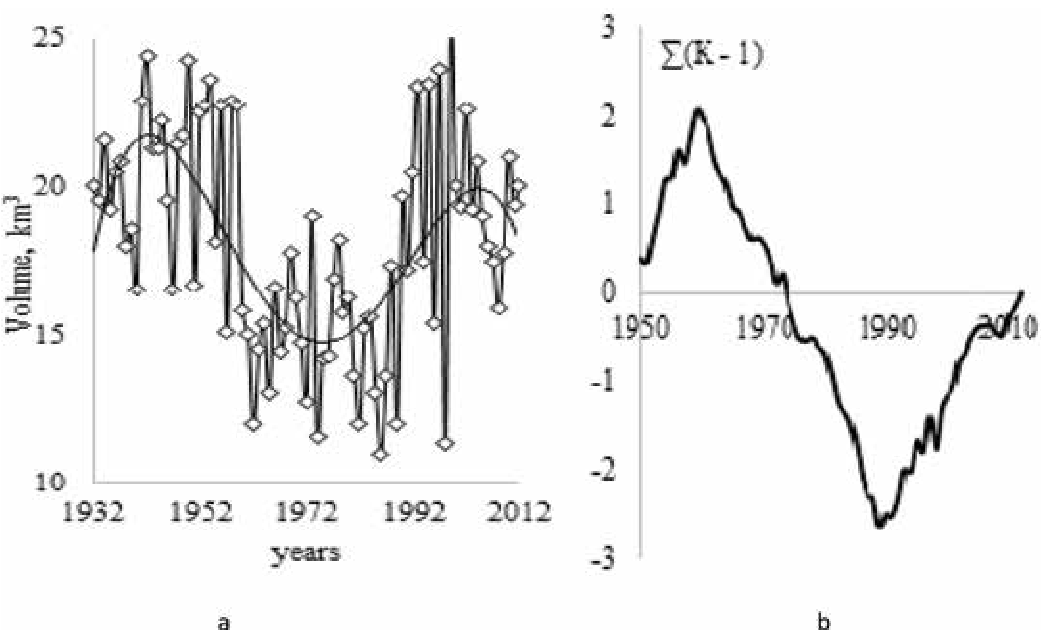

Figure 4. The water volume changes of the Vakhsh River for the period 1932–2012 (a) and the differential integral curve of the Vakhsh River annual average water discharge (b) [6].

The presence of average annual water flows in the differential integral curve allows defining the periods of high and low water availability of the Vakhsh River (**Figure 4b**). It should be noted that the appearance of cyclicality in the water flow of rivers allows predicting the future scenarios of changes in the water flow of the river (**Figure 5a**) [6].

Another important factor in the water flow change is the meteorological condition of the river basins. The analysis of the date from meteorological stations shows that in the Vakhsh River Basin (including the basins of the tributaries of the river) the change in temperature has an increasing trend (**Figures 5b** and **6**). On the other hand, as it is shown in **Figure 6b, d**, atmospheric precipitation on the Kyzilsu River Basin has a decreasing trend with almost constant value on the Obikhingou River Basin.

As it was noted earlier, for the period 1960–2012, the water runoff in most of the rivers of the Vakhsh River Basin has an increasing trend. Thus, the increase in water volume and the decrease in precipitation give reason to believe that there is a continued reduction in the size of the glaciers in the Vakhsh River Basin [6].

3.2. Zeravshan River Basin

The deviation of average annual temperature at Zeravshan Glacier for the period 1931–1961 (a) and 1981–2011 (b) is presented in **Figure 7**. The period 1931–1961, as it can be seen from **Figure 7**, is characterized by low temperature and by high levels of precipitation in the form of snow. This suggests that the meteorological conditions during the period 1931–1961 were favorable for increasing the mass of the glacier [6].

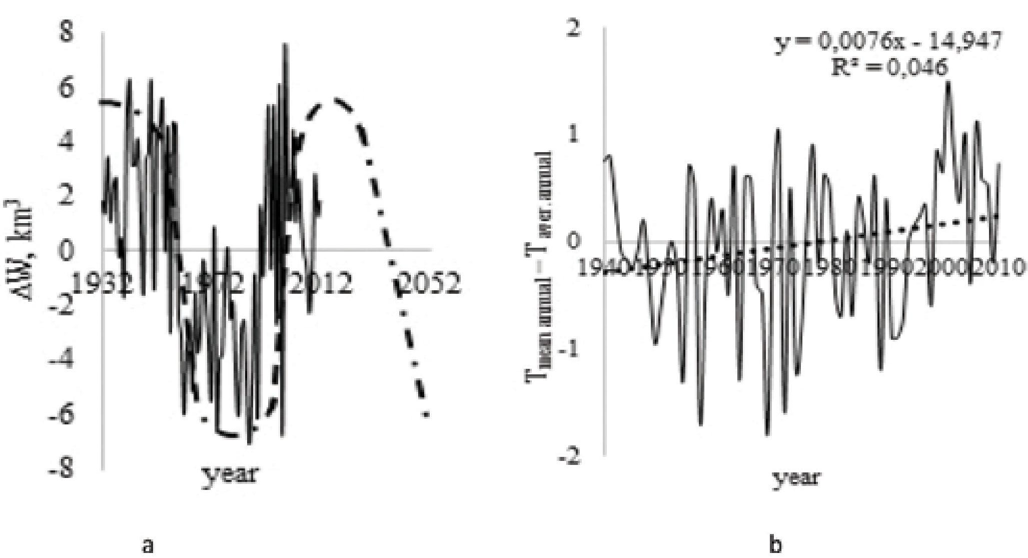

Figure 5. Cycle of the Vakhsh River water flow for the period 1932–2012 (a) and dynamics of the temperature change in the Vakhsh River Basin (Meteostation Garm) (b).

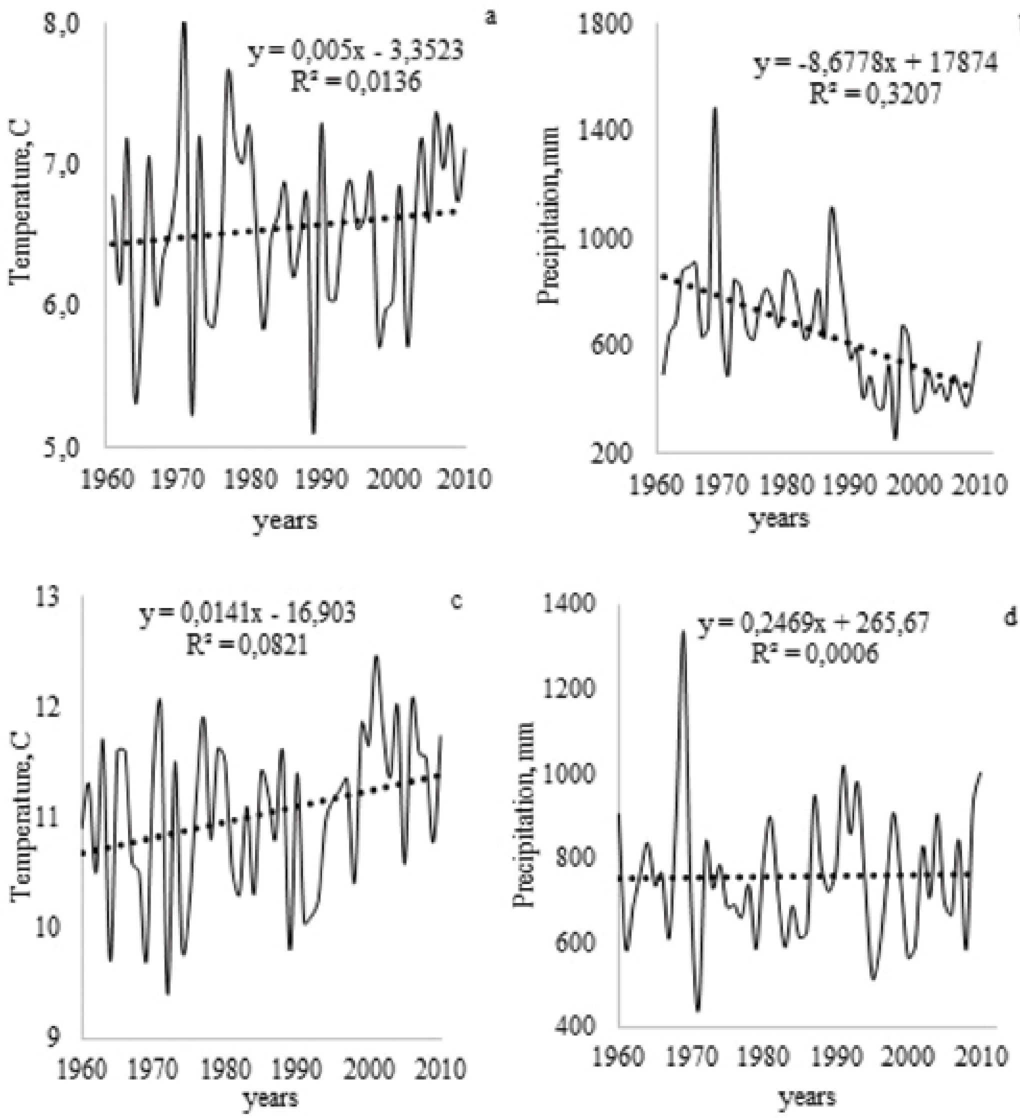

Figure 6. The average annual precipitation and temperature according to meteorological stations Lyakhsh (a, b) and Tavildara (c, d) for the period 1960–2012 [6].

The trend in temperature reversed during the period 1981–2011 compared to 1931–1961 (**Figure 7b**) and precipitation remained almost constant. The temperature change of the Yagnob River Basin for the period 1931–1961, as it is shown in **Figures 7c** and **6d**, is similar to the Zeravshan River basin and has a near-constant value. A significant increase of the temperature is appears for the period 1981–2011 [6].

The average annual water discharge of the Zeravshan River for the periods 1931–1961 and 1981–2011 is presented in **Figure 8a** and **b**. The decreasing trend of water discharge for the

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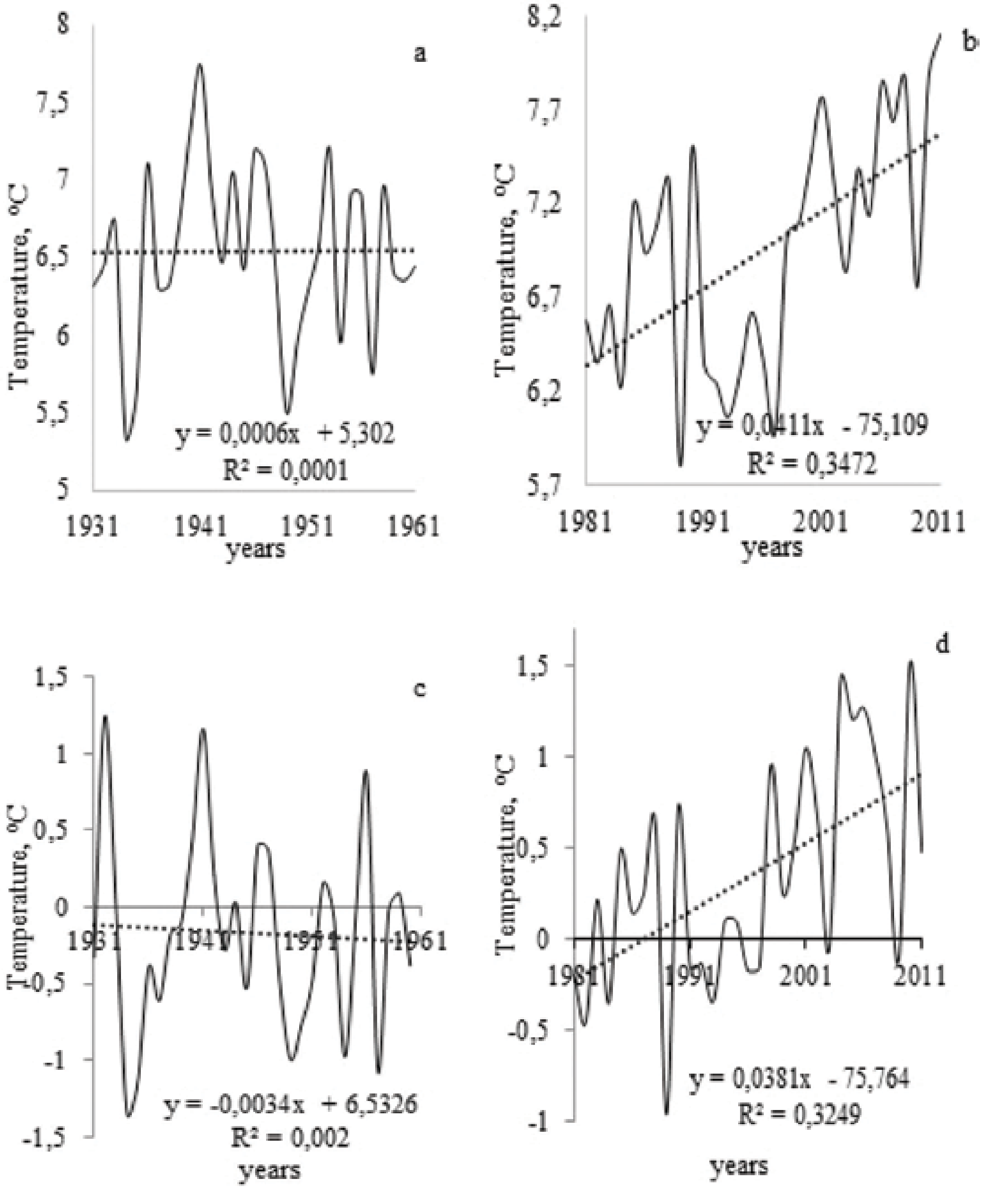

Figure 7. The average annual temperature for the periods of 1931–1961 and 1981–2011 in the area of the glacier Zeravshan (a, b) and in the Yagnob River Basin (c, d).

period 1931–1961 can be explained by the low and near-constant value of the temperature resulting in the snow accumulating and expanding the glacier rather than melting and contributing to river flow. This interpretation is supported by the fact that Yagnob River water flow has been almost constant during period 1931–1961 (**Figure 8c**). A completely different pattern in runoff is observed for the period 1981–2011 which experienced a significant increase in water discharge (**Figure 8b**) [6].

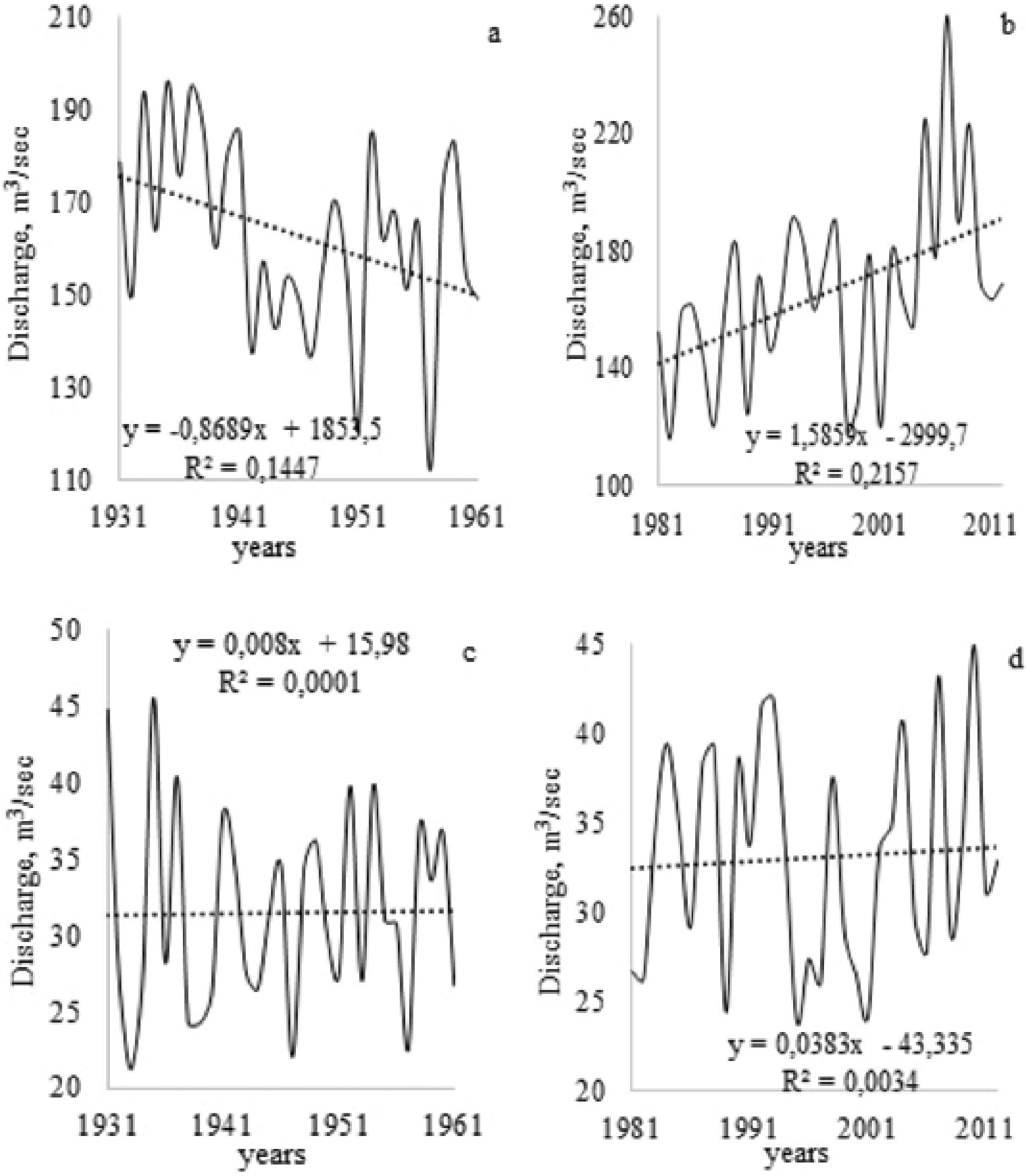

Figure 8. The water discharge value of the Zeravshan (a, b) and Yagnob (c, d) Rivers for the periods 1931–1961 and 1981–2011, respectively [6].

The hydrographs of the Zeravshan (a) and Yagnob (b) Rivers for the periods 1931–1961 and 1981–2011 is shown in **Figure 9** that demonstrate that for the Zeravshan and Yagnob Rivers water discharge is the maximum in July and June, respectively [6].

The period 1981–2011 for the Zeravshan River (**Figure 9a**) is characterized by a flow reduction compared to the period 1931–1961. According to the estimated data, the mean annual runoff for the period 1981–2011 is 5.36 km^3 compared to 6.08 km^3 of the period 1931–1961, that is a decrease of the mean annual runoff by 12%. The mean annual flow of the Yagnob River for the periods 1931–1961 and 1981–2011 are 1.02 and 1.04 km^3 respectively, an increase of no more than 2% [6].

Impact of climate change on the water flow was calculated for Zeravshan River based on the deviation of annual runoff from the mean (**Figure 9**) [6]:

$$\Delta Q = Q_i – Q_o$$

where, Q_i is total water flows for *ith* year and Q_o is the mean annual water flow for the period 1931–2011.

The trends in the flow of the Zeravshan River for the periods 1931–2011(a), 1931–1961 and 1981–2011 are shown in **Figure 10b** and **c** [6].

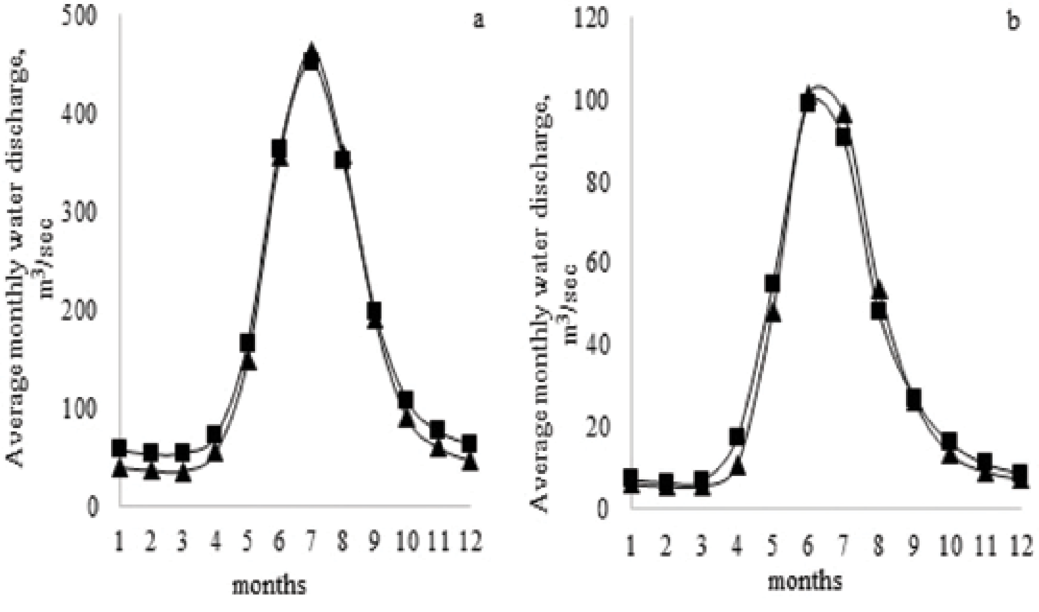

Figure 9. The hydrograph of the Zeravshan (a) and Yagnob (b) Rivers for the periods 1931–1961 (▲) and 1981–2011 (■) [15].

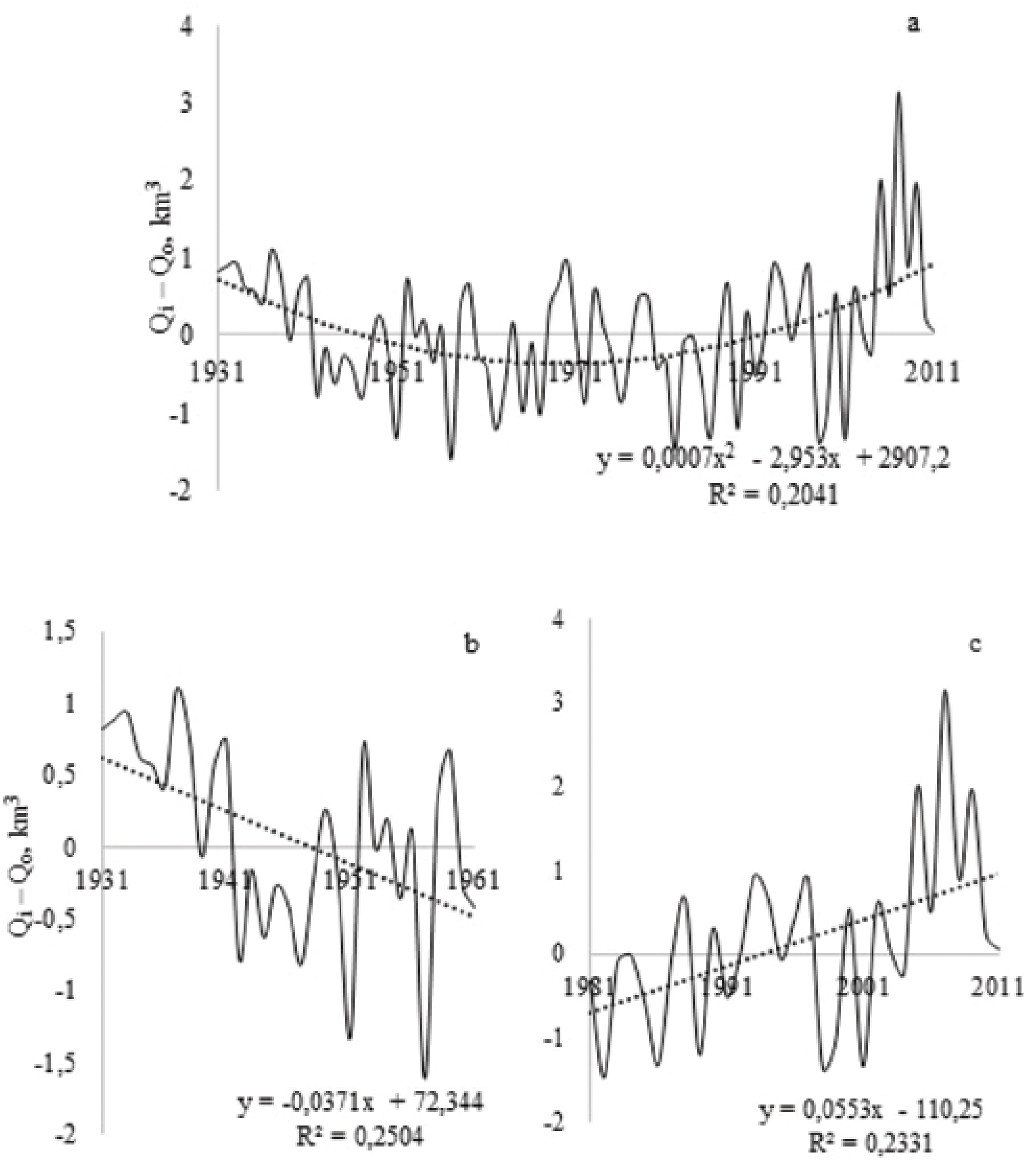

Figure 10. The actual water content of the Zeravshan River (a) for the period 1931–2011(a) and for the periods 1931–1961 (b) and 1981–2011 (c) [6].

A comparison of the Zeravshan glacier meteorological conditions for the periods 1931–1961 and 1981–2011 shows a changing trend in temperature. If the period 1931–1961 was characterized by almost constant temperature, significant increases were observed for the period 1981–2011(**Figure 7**). A similar situation was evident in the Yagnob River Basin. The reduction of water flow in the Zeravshan River for the period 1931–1961 changed to a significant decrease during the period 1981–2011 from 6.08 to 5.36 km^3 [6] (**Figure 11**).

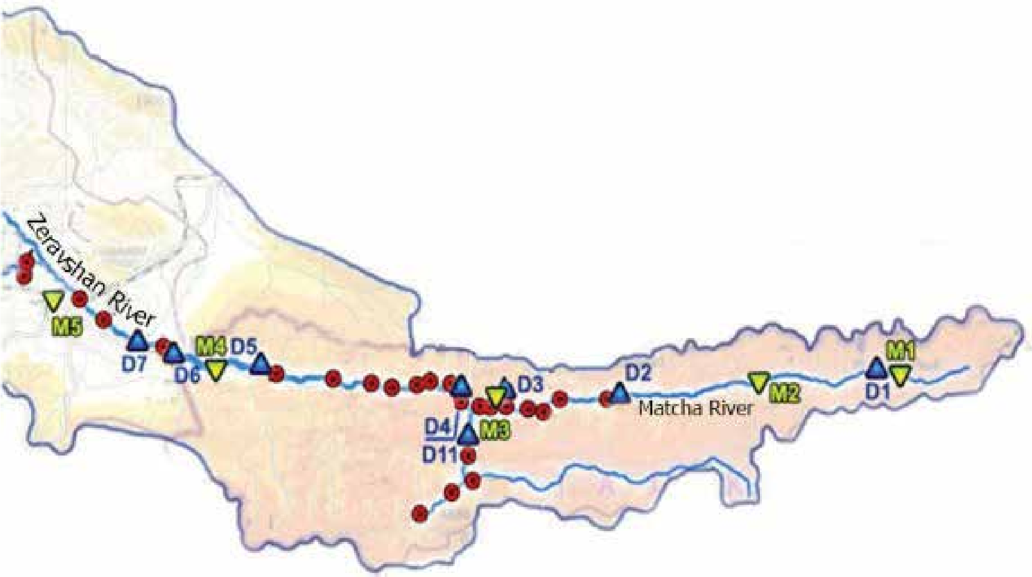

Figure 11. Water sampling side of the Zeravshan River and its tributaries [10, 11].

4. Hydrochemical and ecological aspects

Water quality has become a global issue. Every day, millions of tons of inadequately treated sewage and industrial and agricultural wastes are poured into the world's waters. Every year, lakes, rivers and deltas take in the equivalent of the weight of the entire human population—nearly 7 billion people—in the form of pollution. Every year, more people die from the consequences of unsafe water than from all forms of violence, including war—and the greatest impacts are on children under the age of five [21].

From the international level to watershed and community levels, laws on protecting and improving water quality should be adopted and adequately enforced, model pollution-prevention policies disseminated and guidelines developed for ecosystem water quality. Standard methods to characterize in-stream water quality, international guidelines for ecosystem water quality and priority areas for remediation need to be addressed globally [21, 22].

4.1. Zeravshan River Basin

The results of chemical analyses of the Zeravshan River are presented in **Figure 12** which shows that the difference of the chemical content values of cations and anions of the Zeravshan river water before and after the Anzob mountain-concentrating combine (AMCC) wastewater dams is insignificant and does not exceed their maximum permissible concentration (MPC). It is obvious that the Zeravshan River is not polluted by wastewater of the AMCC [10].

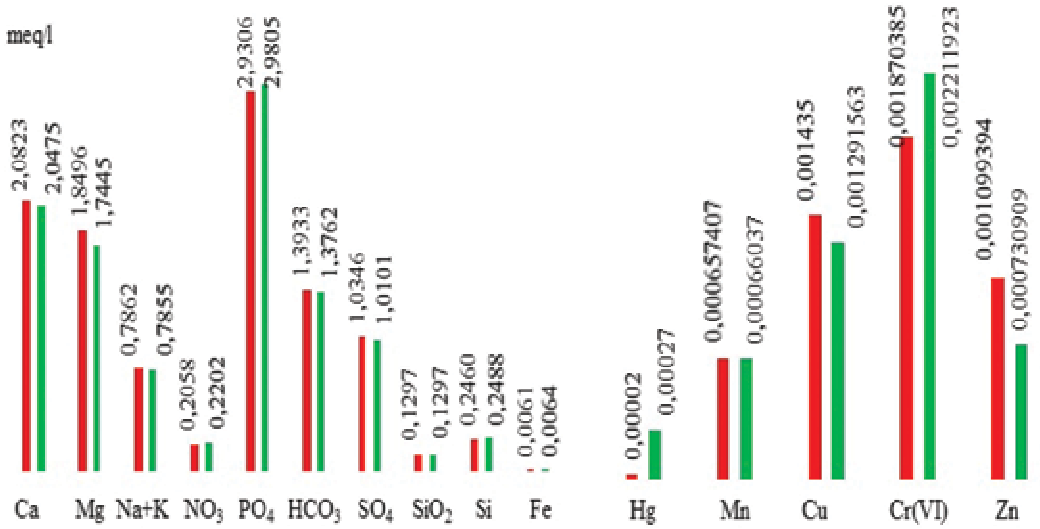

Figure 12. Results of chemical analyses of the Zeravshan River waters up to (■) and after (■) wastewater dams of Anzob mining plant [10].

The orographic feature due to the limitation of underdeveloped irrigated land determines the agriculture level on upstream of the Zeravshan River. Therefore, it can be expected that the runoff flow of collector-drainage water with high salinity to the river is negligible. An analysis of the histogram data (**Figure 12**) of the water composition shows that the Zeravshan river and its tributaries do not experience anthropogenic pressure in the upper reaches, and their mineralization is mainly due to the flushing of water coastal mineral deposits.

A similar phenomenon is observed while analyzing the content of heavy metals and distribution of heavy metals in the snow cover on the glaciers on the southern slope of Mount Elbrus due to their transport to long distances in the form of microparticles by an airflow [23]. Apparently accumulated contaminants in the snow cover and glacier during the melting process reach the river and spread out over long distances.

The choice of snow cover as a natural indicator to air pollution is actual because the snow effectively absorbs impurities from the atmosphere and deposits dry dust emissions from anthropogenic sources [24]. The concentration of pollutants in the snow is 2–3 orders higher than in the atmosphere. This allows measurement of the content by quite simple methods with a high degree of reliability [25]. In order to have information about the chemical composition formed from glaciers' water flow in the formation zone, a complex of physical and chemical analyses of seasonal snow on the glaciers of the Zeravshan, Rossinj and Tro of the Zeravshan River Basin and tributaries of the Zeravshan River emerging from these glaciers was conducted. The river Zeravshan, one of the major rivers of Central Asia, originates at a height of 2775 m. The annual flow of the Zeravshan River is on average about 5.2 Bln. m^3.

According to **Figure 13**, in seasonal snow on the Zeravshan, Rossinj and Rama glaciers a domination in anions SO_4^{2-}, NO_3^-, Cl^- and cations Ca^{2+} and Mg^{2+} is observed.

The isotopic composition (δ^2H, $\delta^{18}O$) and deuterium excess is an informative indicator for hydrological and glaciological researches.

The isotopic analyses of water samples from the tributaries of the Zeravshan River: Sabag, Yarm, Samjon, Tro, Dehavz, Dihadang, Gusn and Dashtioburdon. Were carried out according to the methodology developed at the University of Colorado in Boulder. Analysis was performed on Wavelength-Scanned Cavity Ringdown Spectroscopy (WS-CRDS) and the isotopic composition of hydrogen and oxygen expressed in relative terms δ^2H and $\delta^{18}O$ [20]:

$$\delta = \left[\left(R_{sample}/R_{standard}\right) - 1\right] \cdot 1000‰$$

where R_{sample} and $R_{standard}$ relations 2H/1H and $^{18}O/^{16}O$ in the measured sample and the standard.

The standard is ocean water (SMOW, Vienna, IAEA). Measurement precision was ±0.05‰. At the isotopic analyses it was found that the upstream tributaries of the Zeravshan river

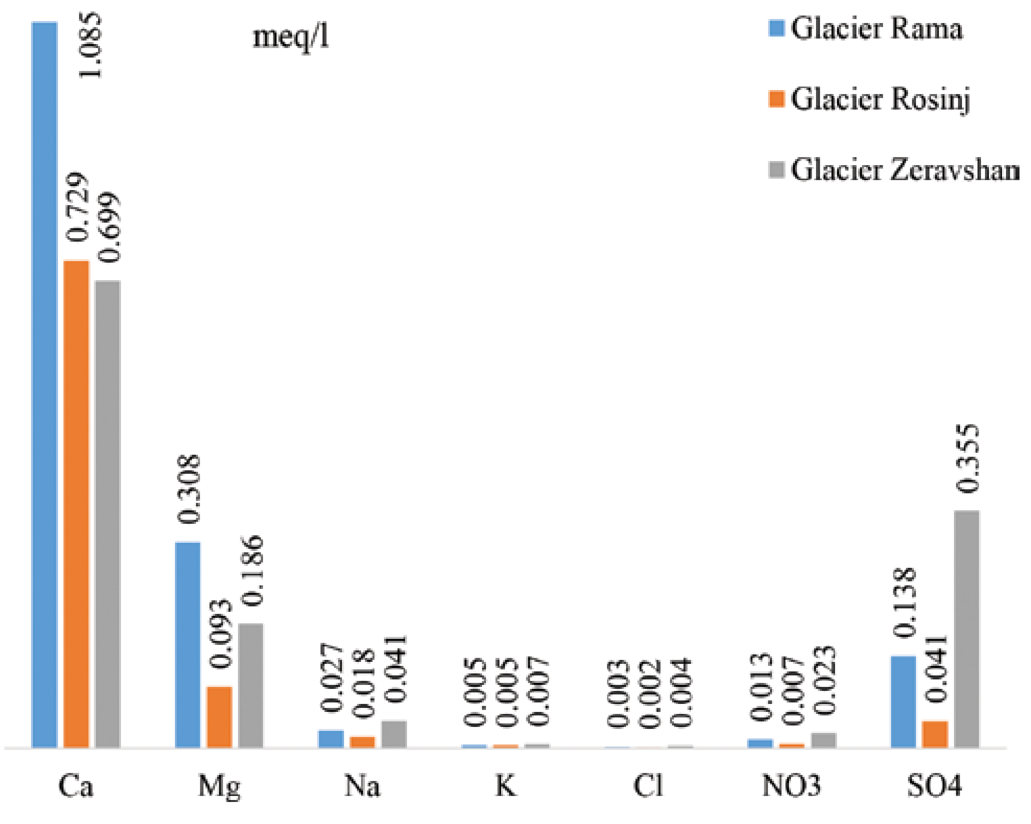

Figure 13. Chemical composition of seasonal snow on glaciers of the Zeravshan River Basin.

are characterized by light isotopic compositions of the oxygen and hydrogen isotopes: $\delta^{18}O$ (−13.23: −13.43) ‰, $\delta^{2}H$ (−88.92: −88.32) ‰ and deuterium excess 16.92—19.21. This suggests that the observed fractionation is a result of the freezing and the accumulation that occurs in winter. In turn, the downstream tributaries of the Zeravshan river have the following isotopic composition: $\delta^{18}O$ (−11. 98: −11.61) ‰ and $\delta^{2}H$ (−78.45: −75.80) ‰. The obtained results indicated the existence of seasonal variations in the isotopic composition of precipitation and their influence on the isotopic composition of the river, in other words, the change of the ratio of rainwater, meltwater from seasonal snow and underground waters [10].

The location of tributaries of the Zeravshan River is shown in **Figures 14** and **15**. The comparison of the isotopic analyses results (**Figure 14**) with the scheme of location of the Zeravshan tributaries shows that as you move from the upstream to the downstream is the weighting of the isotopic composition of water of the relevant tributaries of the Zeravshan River. The main factor of this process is to increase the temperature and therefore the evaporation of water from the rivers [10].

Currently the Zeravshan River irrigates about 551 Th. ha agricultural lands (13% of the total area of irrigated lands of Uzbekistan). One of the most important indicators of the Zeravshan River in the downstream is the salinity that often reaches maximum values of up to 3.0 MPC. This trend continued during the entire annual cycle [26, 27]. The main source of pollution of the river Zeravshan on the territory of Uzbekistan is agricultural drainage water from irrigated lands [26, 28, 29].

A degree of mineralization was determined by measuring the electroconductivity of the water. The values of the electroconductivity of water in different parts of the flow of the Zeravshan river and drainage channels on the territory of the Republic of Uzbekistan shows the extreme values in the collectors and canals that indicate high degree of soil salinity (**Figure 16**).

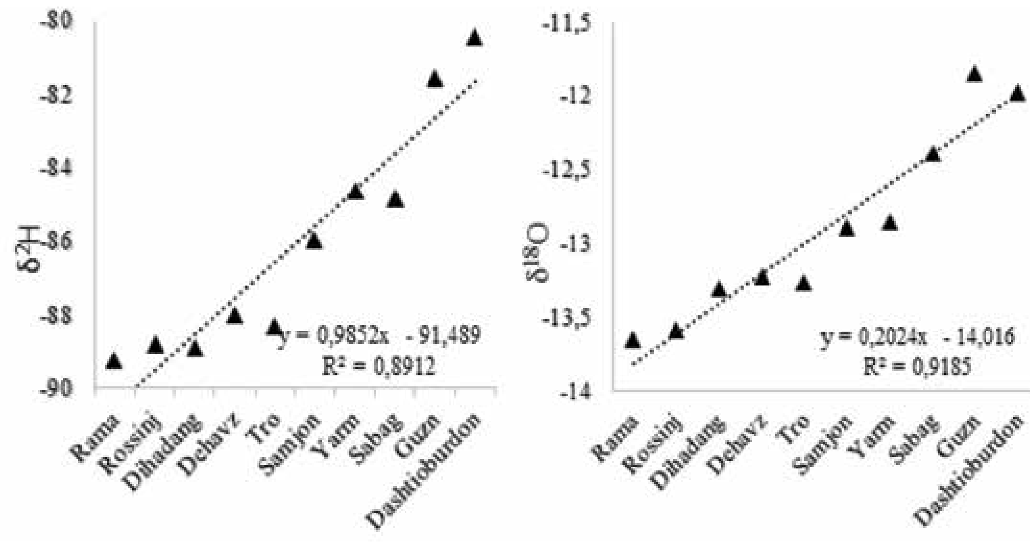

Figure 14. The values of hydrogen $\delta^{2}H$ and oxygen $\delta 1^{8}O$ isotopes for the Zeravshan River tributaries.

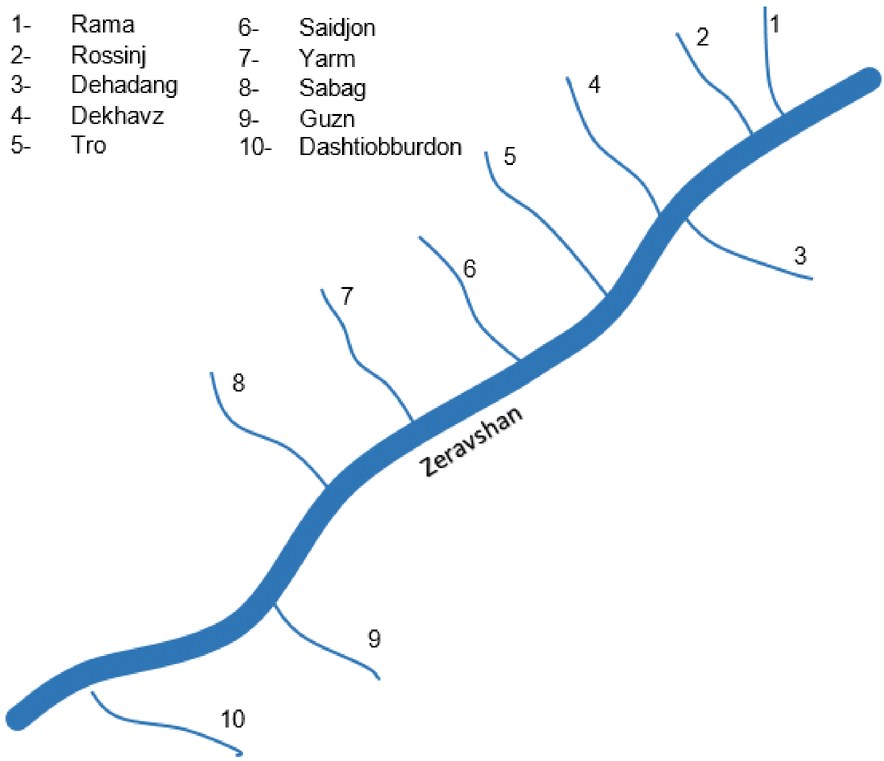

Figure 15. Scheme of the Zeravshan River tributaries location [10].

The change of the concentration of NO_3- along the entire length of the Zeravshan River with the exception of collectors and canals in the downstream of the river shown in **Figure 17**.

Point 13 in **Figures 16** and **17** corresponds to the section of the river on the border of Tajikistan with Uzbekistan. As can be seen in **Figure 16**, electroconductivity of water on the territory of Tajikistan is characterized by a minimum value 240 μS/cm and after crossing the border there is a sharp increase in electroconductivity of water. The results indicate that mineralization of the Zeravshan river water mainly occurs in a downstream of the river on the territory of Uzbekistan.

4.2. Vakhsh River Basin

Monitoring of the Transboundary rivers water quality, identifying sources of anthropogenic pressure and taking adequate measures to eliminate them by the development of modern methods are effective tool for regulating the relationship between the components of the geoecosystem [10]. The chemical composition of the Vakhsh River and its tributaries have been studied by sampling the waters at the points indicated in the scheme (**Figure 18**).

The scheme of water sampling shows the respected individuality of each tributary from the point of view of chemical composition by sampling of tributaries' water up to the confluence

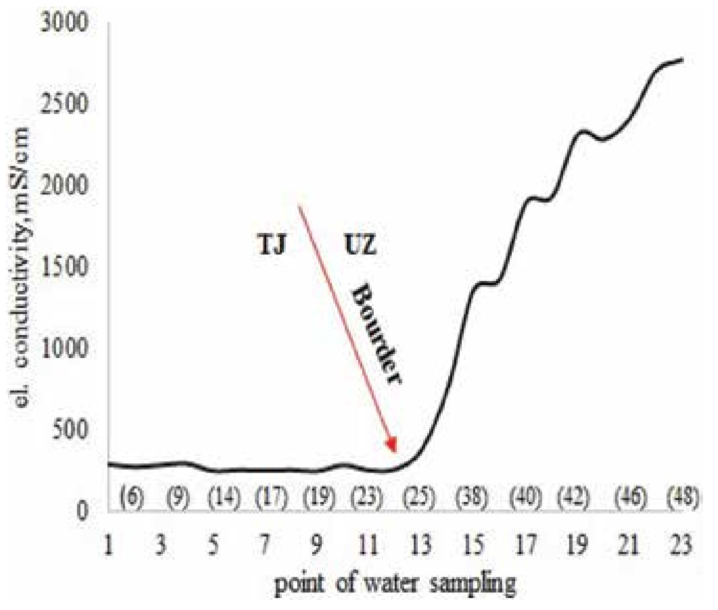

Figure 16. The electroconductivity change of the water in the upstream and downstream of the Zeravshan River *(Numbers in brackets points sampling in the diagram in* **Figure 11***)*.

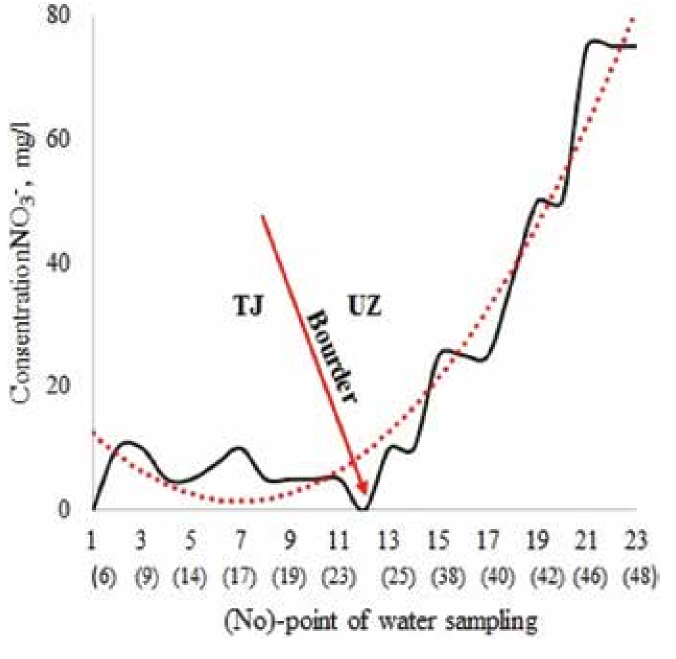

Figure 17. The NO_3- concentration along the entire length of the Zeravshan River *(Numbers in brackets points sampling in the diagram in* **Figure 11***)*.

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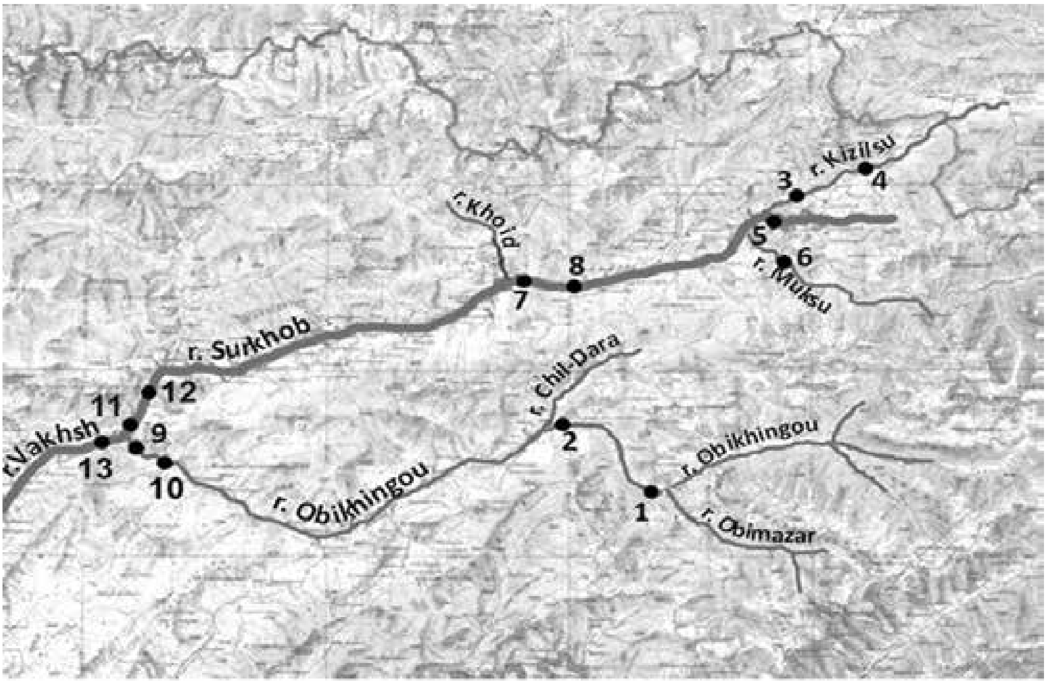

Figure 18. Scheme of sampling of water from the Vakhsh River and its tributaries [10].

with the main stream of the river and up to the junction with another tributary. We carried out chemical analysis of rivers water and groundwater of the rivers' basin, the results of which are present in **Figure 19a, b**, respectively [10].

The content of the chemical elements of the Vakhsh River is shown in **Figures 19** and **20** that indicate that they do not exceed established maximum permissible concentration. This suggests that formation of chemical composition of the Vakhsh river water is mainly due to leaching of mineral rocks [10].

The results of isotopic analysis of the Vakhsh River and their tributaries are presented in **Figure 21** [10].

For interpretation of the isotopic analysis results of the Vakhsh River and its tributaries, we analyze the state of glaciation in the river basins. In the Surkhob River Basin, there are intensively melting small glaciers of the Northern slopes in the Western part of a ridge of Peter the Great. On the southern slopes of the Alay Ridge, glaciation decreases slower as there are larger glaciers. In the Obikhingou River Basin, the largest glacier Garmo is intensively melting [10].

During the twentieth century, it became shorter by almost 7 km, having lost more than 6.0 km^2 in area. It is currently retreating at an average speed of 9 m/year, and the surface settles due to the melting of up to 4 m/year. Another glacier in the same basin, Skogach, retreats annually at 11 m [10].

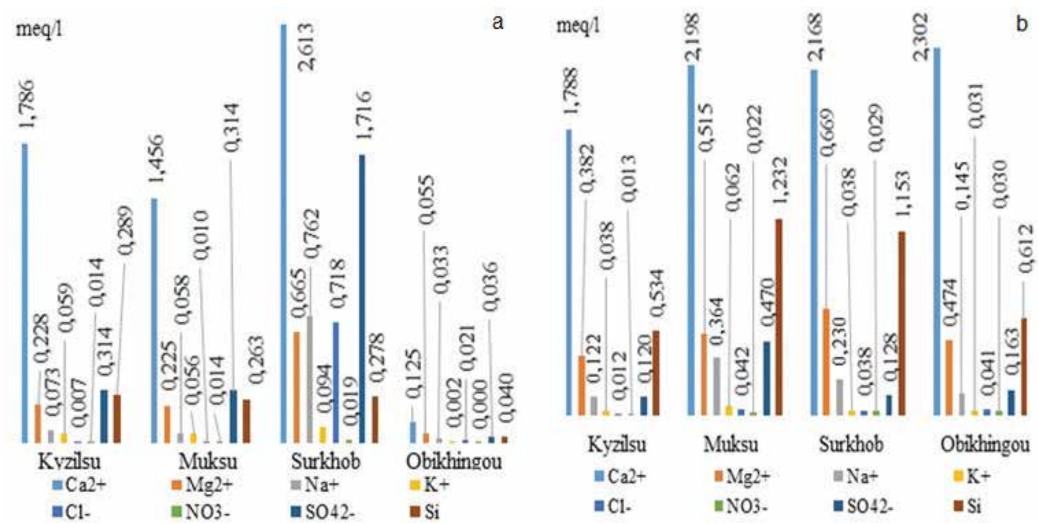

Figure 19. The results of chemical analysis of the waters and groundwaters of the Vakhsh River tributaries [10].

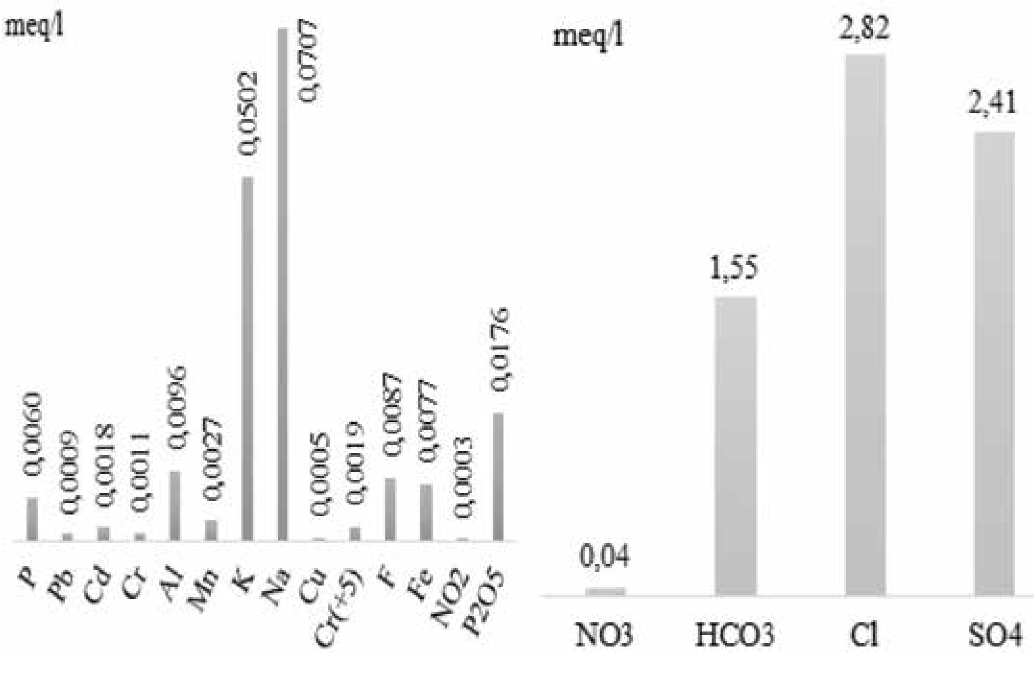

Figure 20. The results of chemical analysis of the Vakhsh River waters.

In view of this, it can be approved that the rivers and Surkhob Obikhingou are fed by glaciers [10] and it can be assumed that precipitation mostly occurs in winter and isotopic compositions are significantly lighter [20].

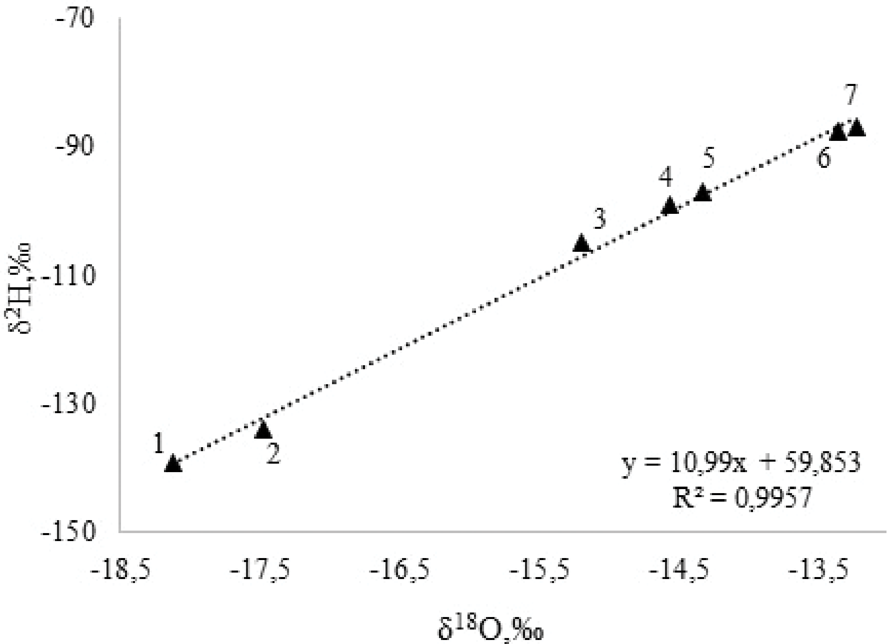

Figure 21. The isotopic composition of water in the Vakhsh River and tributaries: 1, 2: Garmo glacier; 3: Surkhob river; 4: Vakhsh river; 5: Obikhingou river; 6: Kyzilsu river; 7: river Muksu [10].

The weather and climatic conditions of the Vakhsh valley are warmer than in the valleys of its tributaries Surkhob and Obikhingou and consequently due to the evaporation process would have a heavy isotopic composition. However, the contribution of the water tributaries leads to the fact that the isotopic composition of water of the river Vakhsh becomes lighter [20].

The isotopic composition of the Kyzilsu River is characterized by values $\delta^{18}O = -13.36‰$, $\delta^{2}H = -87.88‰$ which is close to the values of the isotopic composition of the water areas with an average annual temperature above 0°C (**Figure 22**). It was found that the isotopic composition of the Naryn River depending on the season changes in the following range: spring ($\delta^{18}O = -13.4‰$; $\delta^{2}H = -96‰$) and autumn ($\delta^{18}O = -12.4‰$; $\delta^{2}H = -89‰$) [20, 28, 30]. Consequently, it can be concluded that to formation of water flow of the Kyzilsu River contribution of glacial runoff is small and mainly occurs due to seasonal rains [20].

Previously [20, 31], by analyses of the chemical composition of river water and groundwater in the river basins of Tajikistan, the processes of enrichment of underground water reservoirs by chemical elements of river water was suggested. Such a mechanism but in the opposite direction, that is, the conversion of reservoirs of underground waters to the source of water for the river, for example, for the Muksu River Basin, was observed.

The results of the isotope analyses of spring waters and groundwater basins of the rivers Muksu, Kizilsu, Surkhob and Obikhingou is shown in **Figure 22**. From **Figure 22**, we can see that the groundwater and spring water of the basin of the river Muksu by the values of the

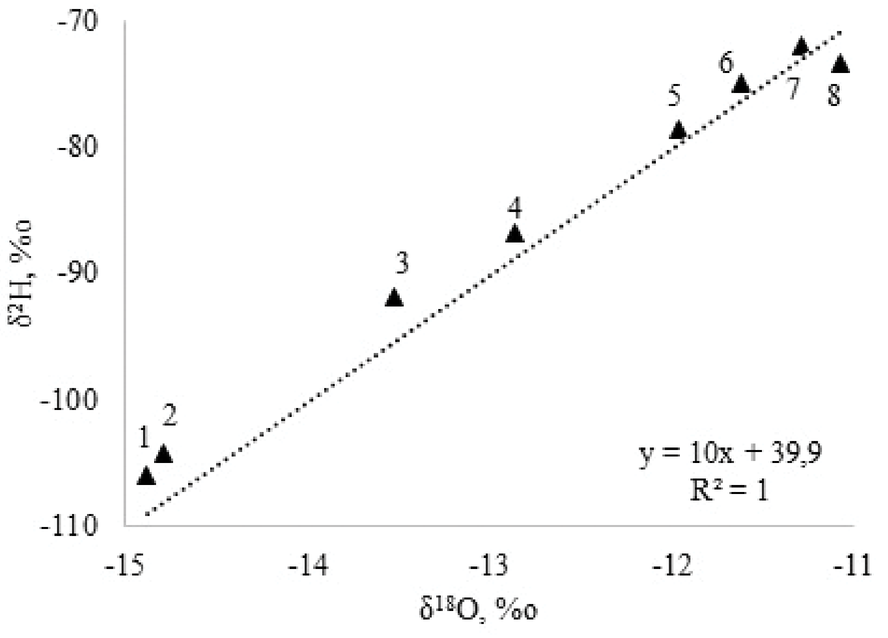

Figure 22. Isotopic analysis of spring (1, 3, 4, 5) and underground waters (2, 6, 7, 8) the basin of the rivers Muksu, Kizilsu, Surkhob, Obikhingou, accordingly [20].

isotopic composition is significantly lighter on average composition of river water and is close to the values of melted glacier water. During spring, snowmelt by the processes of infiltration, underground reservoirs are accumulated melt water and at dry periods turn to sources of runoff formation of river. Of course, it will affect the isotopic composition of river water [20].

5. Conclusion

Now the priority areas for the Central Asian countries are water and the effects of climate warming. The continued degradation of mountain glaciations, growing rate of population in the region and the problem of water supply of the population and economy branches have stimulated the search of scientific mechanisms, approaches to sustainable development at the national level and the solution to the problem of conflict-free use of water resources of transboundary river basins.

Integrated water resources management can play a key role in reducing tensions and conflicts between upstream and downstream countries of Transboundary Rivers of Central Asia on water issues, biodiversity and ecology of rivers and the rational use of water resources in the region. Certainly, the degree of implementation and effectiveness of integrated water resources management is mainly determined by the availability of reliable meteorological, hydrological and glaciological information and the degree of interchange between the countries of the region. High-level saturation of climatic information is achieved only at a continuous and consistent monitoring of climatic parameters of the region.

The results of the monitoring of meteorological and hydrological parameters of river basins of Zeravshan, Vakhsh and Pyanj major tributaries of the Amu Darya show the individuality of each of them, demonstrating the significant influence of mountain orography on the development of climatic features. Therefore, the achievement of reliable data in such conditions is possible in the presence of a developed network of meteorological and hydrological stations in river basins.

It is demonstrated by chemical analyses that the Zeravshan River and its tributaries in the upper reaches do not experience anthropogenic pressure and their mineralization is mainly due to the flushing of coastal water mineral deposits. Chemical analysis of the Zeravshan River water samples before and after the AMCC is shown in the insignificant effect of wastewater factory on water quality. The content of heavy metals in the river does not exceed maximum permissible concentration. The existence of seasonal variations in the isotopic composition of precipitation and their influence on the isotopic composition of the Zeravshan River water is observed. The isotopic analyses show weighting of the isotopic composition at moving from the upstream to the downstream of the Zeravshan River tributaries. The main factor of this process is to increase the temperature and therefore the evaporation of water from the rivers. The content of the chemical elements of the Vakhsh River shows that they do not exceed established maximum permissible concentration. This suggests that formation of chemical composition of the Vakhsh river waters is mainly due to leaching of mineral rocks.

The results of the isotope analyses of spring waters and groundwater of the Muksu River Basin show that groundwater and spring water of the basin of the river Muksu by the values of the isotopic composition is significantly lighter when compared to river water and close to the values of melted glacier water. During spring, snowmelts at infiltration in underground reservoirs are accumulated melt water and at dry periods turn to sources of runoff formation of river. Of course, it will affect to the isotopic composition of river water.

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Section 4

Water Governance

Chapter 10

Information-Communication Technologies as an Integrated Water Resources Management (IWRM) Tool for Sustainable Development

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Additional information is available at the end of the chapter

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Abstract

Sustainability is a crucial and at the same time vital approach for satisfying future generations' rights on natural resources. Toward this direction, global policies, supported by international organizations such as UNESCO and its international science programs, foster sustainable development as principal concept for the management of various thematic areas including the environment. The present work promotes the integration of information-communication technologies (ICTs) in the water resources management field as a state of the art concept that sets the basis for sustainable development at global scale. The research focuses on the ICTs contribution to the evolution of scientific and technological disciplines, such as satellite earth observations, real time monitoring networks, geographic information systems, and cloud-based geo information systems and their interconnection to integrated water resources management. Moreover, selected international research programs and activities of UNESCO International Hydrology Programme (IHP) are synoptically but comprehensively being presented to demonstrate the integration of the technological advances in water resources management and their role toward sustainable development.

Keywords: water resources, integrated management, sustainability, information-communication technologies, UNESCO-IHP

1. Introduction

Water is at the heart of sustainable development, i.e., integration of economic, socio-political, and ecological/environmental conditions for humans' development [1–3]. Currently, apart from the Goal 6 "Clean Water and Sanitation" of UN Sustainable Development Goals (SDGs) of the 2030 Agenda for sustainable development, water is included in various targets of the other Goals and is essential in achieving majority of SDGs [4]. Water resources, and the range of services they provide, underpin poverty reduction, economic growth, and environmental sustainability [3], as well as water is fundamental for adaptation to climate change.

However, water management and allocation apart from the current competing demands, such as water supply, agricultural irrigation, hydropower production, and ecosystems preservation, will be further affected mainly by demographic and climatic changes drivers that increase the stress on water resources [5, 6]. According to United Nations World Water Development Report [2], the 90% of the 3 billion people to be added to the population by 2050 may be in regions already experiencing water stress and with no sustainable access to drinking water. In terms of climate change, although humans historically developed settlements in floodplains, they continue to do so [7], in controversy of the adverse impacts, such as storm surges, sea level rise, and coastal flooding and inland flooding in some urban regions that are denoted in the IPCC RCP 8.5 scenario [8]. Even if developed countries are proceeding to the management of flood risk and the reduction of potential damages, i.e., the mapping of flood hazard areas and the generation of Digital Flood Insurance Rate Maps (DFIRMS) in the United States and the adoption of the Flood Directive in 2007 in the European Union that requires member states to assess the risk of flooding, to map potential flood extent, and to coordinate efforts to reduce flood risk [9], at global scale flood events can be considered one of the most consistent and recurring natural disasters experienced by human populations. Moreover, the IPCC RCP 8.5 scenario also designates that the frequency and magnitude of meteorological droughts in presently dry regions by the end of the twenty-first century are likely to be increased [10].

When dealing with transboundary waters, their management confronts augmented difficulties that could be comprised to the lack of (i) political willingness for cooperation, (ii) communication channels among decision makers, scientists, and stakeholders, and (iii) effective exchange mechanisms of data and information [11]. In the literature [2, 12], different models of collaborative activities for transboundary water resources management have been suggested. Even if the approach used in these models differs, depending on which particular scientific discipline or professional community has developed the model, the core element in all models is the data collection and information sharing. Regarding the later, it is mentioned [13] that more than half of the transboundary water agreements that include water resources data and information exchange and were signed in the last 50 years, (i) have direct mechanisms for exchange, with the percentage to present a steadily increase rate, and (ii) the exchange occurs in all geographic regions of the world.

A solution toward these increased threats is the integrated water resources management (IWRM) approach that promotes the way forward for efficient, equitable, and sustainable development and management of the world's limited water resources and for coping with conflicting demands. Implementing IWRM at the river basin level is an essential asset in managing water resources more sustainably leading to long-term social, economic, and environmental benefits [2]. The IWRM approaches include the establishment of an overall water policy and laws at basin scale, creation of water rights, use water pricing in allocation, and stakeholders participation in decision making [14]. On the other hand, although the principles and concepts of IWRM have been widely accepted, the level of integration of IWRM is not satisfactorily progressing in many basins.

Without accurate, intensive, and long-term data acquisition and exchange, the state of the world's water resources cannot be adequately assessed, effective preservation and remediation programs cannot be run, and program success cannot be properly evaluated [15]. The continuous emergence of the information-communication technologies (ICTs), nevertheless, has put new standards in the collection, management, and dissemination of water related data, and the coupling of ICTs with mathematical models is proposed as an adjuvant tool for the implementation of the IWRM concept to different socioeconomic environments. The increased efficient of telemetry monitoring networks in terms of real-time measurement of variable environmental parameters, of data storage capacity and power autonomy together with their decreased cost, of the use of Web-based information systems that facilitate spatial data, descriptive information, and observation data sharing over the cloud and are accessible through common Web browsers, of the plethora of free of charge high resolution remote sensing data, and of the direct or indirect integration of geographic information system (GIS) technology to water management issues and the open source mathematical models and tools are selective examples of the advances that ICTs could offer to the water sector.

The 2030 Agenda represents a significant step forward in terms of recognizing Science, Technology and Innovation (STI) as a driving force for sustainable development in its three pillars, environmental, social, and economic. As the only UN agency that includes science in its mandate, UNESCO finds itself at the heart of this initiative. Regarding the water sector, the UNESCO International Hydrological Programme (IHP) is the only intergovernmental program of the UN dedicated to water research, water resources management and security, education, and capacity building. Since its inception in 1975, IHP has evolved from an internationally coordinated hydrological research program into an encompassing, holistic program to facilitate education and capacity building and enhance water resources management and governance. IHP fosters a transdisciplinary, multidisciplinary, and integrated approach to watershed and aquifer management, which incorporates the social dimension of water resources and promotes and develops international research in hydrological and freshwater sciences. The current phase of IHP (2014–2021) on water security will contribute to the achievement of water-related SDGs and targets.

The aim of this research is twofold and aims at: (i) synoptically presenting the contribution of ICTs advancements in the field of monitoring of the environment and the potentiality derived from cloud technologies and (ii) demonstrating the integration of the technological progress in the UNESCO IHP and UNESCO Chairs programs as a tool to decision makers, policy makers, engineers, researchers, etc., in environmental and management issues. From the following analysis is clearly denoted that ICTs form inextricable part in the integrated management of water resources.

2. Evolution of ICTs and implementation on water related issues

The latest technological developments brought communications at the forefront of the technology advancements. Evolutions on communication, i.e., transfer of any type and form of information with high speed internet networks of global coverage, on computing machines, i.e., transformation of personal computers to powerful workstations as well as cloud computing, and on storage capabilities, i.e., cloud backup and storage services with unlimited utilities, have direct impact on technologies, such as remote sensing, monitoring equipment, data bases, and spatial data analysis, that have traditionally been used for the management of water resources.

2.1. Satellite remote sensing

Over the last decade, significant advances in remote sensing techniques have led to a more complete overview of the water cycle at the global scale. Satellite earth observation can provide direct information to processes such as estimation of evapotranspiration [16], precipitation [17], and snowcover/snowmelt [18, 19]. Indirect methods, such as the coupling of remote sensing data with groundwater models, can be used for the assessment of the infiltration process and the recharge of the aquifers. Launched in 2002, the NASA Gravity Recovery and Climate Experiment satellites (GRACE) is the first satellite mission able to provide global observations of terrestrial water storage changes. Many negative trends have been observed in north-west India [20], the Middle East [21], northern China [22], the Caspian Sea and the Aral Sea regions [23], and the southern part of the La Plata basin [24]. Significant positive trends were found in southern Africa, near the Upper Zambezi and Okavango river basins, as well as in the Sahel and the Niger basin [25] and in the Amazon [26].

Regarding water quality characteristics, satellite RS has been used with high levels of accuracy for monitoring marine and coastal ecosystems [27]. Moreover, the specific technology provides essential information on the functioning of ecosystems and on the environmental change drivers [28]. Earth observation together with national statistics, field-based observations, and numerical simulation models are designated as the main source of information for the global monitoring of ecosystem services [29]. A recent study demonstrated that environmental parameters, such as chlorophyll-a (Chl-a) and total suspended matters (TSM), can be investigated at river basin scale through direct and indirect remote sensed observations [30]. On the other hand, in situ measurements for various ecological parameters are limited to a few experiments sites due to severe economic cost, difficulty in accessing the area of interest and a posteriori highly laborious procedures. Moreover, according to a survey of 52 papers chosen randomly from the journal Ecology, the most ecological sampling is conducted at small spatial scales or consists of infrequent or one-time sampling [31].

In the irrigation sector, satellite earth observation is a useful tool for the retrieval of data that are required for an irrigation system characterization, a process that is necessary for effective water management, as it provides essential knowledge through performance and accounting indicators [32]. In particular, recent advances in satellite earth observation can provide several parameters related to irrigation management, such as the extent of the irrigated area, evapotranspiration [33], biomass and yield estimation [34], and irrigation system performance [35].

A further contribution of remote sensing techniques such as light detection and ranging (LiDAR), interferometric synthetic aperture radar (InSAR), and photogrammetry is the construction of Digital Elevation Models (DEMs) [36]. The latter has been proved as a significant tool both for hydrological and hydraulic modeling procedures. In the first case, a DEM can be used for extracting vital topographic and water targeted information including basin boundaries, area and perimeter, watershed delineation, stream definition, flow direction and accumulation, total length and slopes of stream channels, average stream length ratio, drainage density, etc. All the aforementioned information is introduced in spatial distributed or lumped hydrological models for calculating critical parameters, such as the time of concentration [37] and flow accumulation to the basin outlet.

At the same time, DEMs are currently routinely being used together with hydrodynamic models in order to simulate the inundation area after a flood event. Some authors [38] assess the impact of riverbed geometry mapping techniques, by comparing various terrain models, on the performance of a 1D hydraulic model in predicting the flood events. However, 2D hydraulic models are considered the most modern tool for flood inundation and flood hazard studies, where the hydrodynamic model could be coupled with terrain models in order to offer nearly automated flood mapping results [39]. The latter is proposed by the European Union Directive on the assessment and management of flood risks, as the most appropriate tools for generation of flood hazard maps.

2.2. Real time remote monitoring

Telemetric monitoring systems have long been used in the water sector, for remotely monitoring river flows, water quality, and reservoir level to aid water resources management or assist in flood early warnings [40]. However, it was only the last years that the technological emergence in the fields of (i) electronics and microelectronics, such as advancements in new sensor technologies and automated controls, (ii) energy efficiency and autonomy, e.g., the use of photovoltaic panels coupled with electric batteries which have limited life range, (iii) communication technologies with GPRS/GSM extended coverage, (iv) computer technology with the creation of microprocessors and unlimited storage capabilities, and (v) costs in terms of the large cost decrease trend of the aforementioned technologies, boosted the continuous monitoring capabilities of the telemetric monitoring system. Other researchers, see [31] for example, facilitated the telemetric monitoring technology in order to investigate a natural and isolated lake in Northern Taiwan which was inaccessible for extended periods due to extreme climatic conditions caused by typhoons.

Telemetric monitoring systems consist of two principal components: the field equipment and the base station equipment. The field equipment in general includes measuring sensors, a data logger system for data storage and a modem for data transmission, while the base station includes the database and the appropriate software. At the sensor level, the primary issues are the sensor suitability for placement in a field environment, its cost and its power requirements

[31], with sensors for physical parameters, such as temperature, moisture, light, etc., to be widely available, while nitrate and carbon dioxide sensors have to be currently very expensive and have moderate power requirements. As far water quantity observation is concerned, the use of electronics in water velocity instruments is responsible for the decommissioning of the traditional flow velocity measurements that were based on mechanical propeller velocity meters [41]. The velocity measurements coupled with water level observations were used for establishing a stage-discharge relationship (so-called rating curve) [42], a method that demonstrated several limitations due to changes in the channel geometry or roughness (vegetation for instance). The main reason behind this transition is the higher efficiency and easier operation that the new electronic equipment presents [43]. Currently, the progress that has been conducted in optics, radar, acoustics, and electromagnetism has led to a new generation of flow measurement devices, which can offer greater efficiency and performance to map river hydrodynamics [41, 44]. Toward this direction, the continuous acoustic Doppler current profiler (ADCP) flowmeters are used to measure the bulk velocity in the acoustic beam, with the length of the river reach as well as the width of the river sections not being determining factors for the implementation of the ADCP method [38].

Solutions to the power requirements of telemetry water monitoring systems can currently be given with the integration of solar photovoltaic (SPV) cells to the system infrastructure. The produced power of such systems is more than adequate, since similar approaches have been tested in energy intensive installations such as water pumping with SPV and been implemented around the globe as an alternative electric energy source for water pumping at remote locations [45]. As for the data transmission, it is revealed [46] that mobile phone is covering rural areas where few other services might be available (e.g., grid electricity or piped water supply), while it was estimated that in 2012, more people in sub-Saharan Africa had access to the mobile phone network than to improved water supplies. Consequently, the use of general packet radio service (GPRS) protocol, which is a packet-oriented mobile data service used in 2G and 3G cellular global system for mobile communications (GSM) [47], can satisfy the demands for observed data transmission to the base station.

However, it should be mentioned that sensor networks are not a panacea in data collection, since they are susceptible to malfunctions that can result in lost or poor-quality data [48, 49]. The fact that environmental sensors can be damaged or destroyed both by natural phenomena (e.g., floods, fire, animal activity), and by malicious human activity (e.g., theft, vandalism), as well as the not properly maintenance of the sensors, may produce low-quality data. Therefore, in order to secure the reliability and accuracy of the massive quantities of data that are collected by the automated monitoring networks, these new data streams require automated quality assurance and quality control processes in order to ensure the minimum bias, and because the manual methods are inadequate for the volumes of data and the time constraints imposed by near-real-time data processing [50].

2.3. Geographic information systems

Despite its broad use, GIS technology was not specifically developed for engineering modeling applications, but it was launched as a general tool to store, retrieve, manipulate, analyze, and map spatial data [51]. Nevertheless, it was proved that because of the spatial nature of the required data in water resources modeling and management, GIS can be effectively utilized in both aforesaid water processes [52]. Currently, GIS technology is successfully being combined with surface hydrological models, groundwater models, water supply and irrigations systems, hydrodynamic models for floodplain management, water quality models, water resources monitoring and forecasting, and river basin management [52, 53]. Moreover, at the present state, the vast majority of water related models incorporate modules that are completely linked with GIS software in order both to retrieve the input data and to visualize the final outputs. The Soil and Water Assessment Tool (SWAT) model, for example, is a robust watershed modeling tool that uses the ArcSWAT interface, which is an extension to ArcGIS environment to create its inputs [54]. Similarly, a lot of the models developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC), such as the Ecosystem Functions Model (HEC-EFM), Hydrologic Modeling System (HEC-HMS), and River Analysis System (HEC-RAS), have a set of procedures, tools, and utilities for processing geospatial data in ArcGIS using a graphical user interface (GUI) for the preparation of data.

However, this significant advantage of GIS capability to incorporate related spatial data into traditional water resources databases and then retrieved by water-related models can also be exploited by programming and the development of custom graphical user interfaces (GUI). In other words, GUI is a bridging software that makes the communication links between the GIS databases and the model interface by transforming the data on the format that is required by the model. GUI and query languages permit rapid selection and modification of attribute data and parameter values, allowing for swift sensitivity analyses and multiple scheme evaluation [51].

Prior to performing actual simulation, water resources modeling requires a number of time-consuming steps, including collection, compilation, storage, retrieval, and manipulation of spatial data. With their ability to combine various data sets, GIS software changed the way water resources modeling is handled [55]. In surface water hydrology at river basin scale for example, the data required for the assessment of hydrological parameters such as time of concentration, infiltration rate, etc., depend on a big data set related to the following: geology, edaphology, land uses, land cover, and ground relief. At the same time, the meteorological information usually comes from specific monitoring stations, i.e., point sources, or is given in the form of a mesh. GIS technology enables the coupling of all the previous information in order to be spatially distributed in the hydrological model units and thereafter the model to simulate the rainfall-runoff process [56]. The usefulness of GIS can also be proved when dealing with climate change assessment at river basin scale [57]. In that case, the gridded climate change data were spatially distributed over the hydrological units derived by the MODCOU hydrological model [58] in order to simulate a transboundary river discharges under specific climate change emission scenarios.

2.4. Geo-information cloud databases

The development of cooperative databases has been fostered by the improvement of GIS technology which, among its other capabilities, combines the storage of descriptive and observational information with coverage characteristics [59]. At the same time, with the continuous emergence of new Internet technology, GIS are becoming more open and accessible, thereby facilitating the democratization of sharing spatial data, open accessibility, and effective dissemination of information [60]. Furthermore, the implementation of a relational database management system (RDBMS), which is related to geographical objects through geodatabases, enables the coupling of spatial information with tabulate data in order to store, update, manage, and properly allocate information. This means, for example, that a substance of concern that is recorded by a gauge station of a telemetric monitoring network can be connected to a number of spatial elements, such as the downstream water body, inhabited areas, and environmental protected areas.

In the latest years, both open source (OS) and commercial geo information systems are being routinely used, not only for sharing spatial datasets and monitoring observations but also for advanced geoprocessing functions across the Web [61]. In order to bypass interoperability problems and the data not only be easily accessible but also easily operated, international communication standards, including Open Geospatial Consortium (OGC) standard-compliant services, have been developed to support the establishment of Spatial Data Infrastructures (SDI) [62]. The OGC Web Processing Service (WPS), for example, defines a standard interface to access geoprocessing functions through Web services, while the Catalog Service for the Web (CSW) defines a standard way for publishing and discovering geospatial resources. Similar approaches to the structure of spatial data have been adopted at European level by the INSPIRE Directive of the European Community (EC) [63] that triggers the creation of a European spatial data infrastructure which delivers integrated spatial information services linked by common standards and protocols to users.

The evolution of the WebGIS systems in the early 1990s from the use of the Extensible Markup Language (XML) to the later use of geography mark-up language (GML) and scalable vector graphics (SVG) as well as the integration of Web Feature Services (WFS) and Web Map Services (WMS) to the current WebGIS systems is presented in the literature [64, 59]. Currently, one of the most up to date technologies for spatial information sharing is the Google Fusion Tables (GFTs). GFT is a cloud computing database that provides services on the Web for data management and integration. These services can be accessed directly over the Internet through a browser and permits programmatic access via application programming interface and integration of existing tabular data. The specific technology works by exporting data values from the tables created online or from a user provided spreadsheet and converting it into a meaningful graphical data representation. This collaborative scientific platform has started penetrating into the scientific community. In particular, GFTs coupled with Google Earth were used for time-critical geo-visualizations of the NASA Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Deepwater Horizon oil spill imaging campaign [65]. In this case, the GFT service was applied to create a highly interactive image archive and mapping display, while its Application programming interfaces (API) was utilized to create a flexible PHP-based interface for metadata creation as the basis for an interactive data catalog. Researchers combined GFT with the OGC sensor observation service (SOS), which can provide real-time or near-real-time observations, in order to manage and analyze in situ sensor observations of soil moisture due to its impacts on agricultural and hydrological processes [66]. The literature also shows that GFTs were used for the development of a geo-referenced information system developed for the transboundary aquifers in Africa. The aim of this system was to provide appropriate tools under a Web-based platform for water management institutions in the region [59].

3. ICTs implementation on selective UNESCO IHP case studies

3.1. Remote sensing

Remote sensing precipitation and atmospheric analysis data have been used by UNESCO-IHP in collaboration with Princeton University for the development of an experimental drought and forecast system for Africa, Latin America, and the Caribbean [10] (accessible at http://stream.princeton.edu/). In particular, the historic and real-time data are calculated using the Variable Infiltration Capacity (VIC) land surface hydrological model [67], and the system allows monitoring of meteorological, hydrological, and agricultural droughts in developing regions, where institutional capacity is generally lacking and access to information and technology prevents the development of systems locally. It has the advantage of providing a standardized format for any of the components of the water balance, providing a comprehensive analysis for any point location within the Monitor's domain (currently covering Africa, Latin America, and the Caribbean and the United States), while providing an overview of the regional, transboundary extent of drought hazards.

Similarly, UNESCO-IHP has collaborated with the Center for Hydrometeorology and Remote Sensing (CHRS), University of California, Irvine, on the development of tools to provide near real-time global satellite precipitation estimates at high spatial and temporal resolutions, including the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Cloud Classification System (PERSIANN-CCS) [68]. The specific system is used to inform emergency planning and management of hydrological risks, such as floods, droughts, and extreme weather events, with the Namibia Drought Hydrological Services (NHS), for example, using it to prepare daily bulletins with up-to-date information on flood and drought conditions for local communities.

Moreover, nowadays, ICTs coincide with the mobile phones and APIs blooming. Following this technological trend, in 2016, IHP and the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California-Irvine launched the iRain mobile application, devoted to facilitate people's involvement in collecting local data for global precipitation monitoring (http://en.unesco.org/news/irain-new-mobile-app-promote-citizen-science-and-support-water-management). The specific application allows users to visualize real-time global satellite precipitation observations, track extreme precipitation events worldwide, and report local rainfall information using crowd-sourcing functionality to supplement the data. The specific application works together with the PERSIANN-CSS tool and provides real time observation for the amelioration of the remote sensing precipitation estimations.

Within the framework of its groundwater and climate change programme (GRAPHIC) (http://en.unesco.org/graphic), UNESCO-IHP undertook an in-depth assessment of climate variability impacts on total water storage across Africa using a simplified water balance model and

GRACE satellites observations. Results indicate that rainfall patterns associated to the North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO) are the main drivers of inter-annual water storage changes in Northern Africa and Sub-Saharan Africa, respectively. The Atlantic Multidecadal Oscillation (AMO) plays a significant role in decadal to multidecadal variability, particularly in the Sahel. The findings of this study could be beneficial to decision-makers and help to adequately prepare effective climate variability and adaptation plans (e.g., managed aquifer recharge—MAR) both at national and transboundary level through river basin organizations.

3.2. Monitoring networks for water

On the field of monitoring networks, the importance of groundwater resources is denoted by the Global Groundwater Monitoring Network (GGMN). GGMN is a participative, Web-based network of networks that was set up to improve quality and accessibility of groundwater monitoring information and subsequently the knowledge on the state of groundwater resources at global scale. GGMN is a UNESCO IHP programme, implemented by the International Groundwater Resources Assessment Centre (IGRAC) and supported by many global and regional partners. The GGMN portal (https://ggmn.un-igrac.org/) contains information on the availability of groundwater monitoring data through space and time, and through the portal, groundwater level data and changes can be displayed on a regional scale.

Users are allowed to upload, interpolate, and analyze the groundwater data using the following options:

- Representative groundwater point measurements can be uploaded as well as can be transferred from a national system via Web services, while the data can be displayed showing the mean, range, or change in groundwater level for a selected time period.
- Point measurements can be combined with proxy information and personal expertise to create groundwater level maps. Produced groundwater maps can be shared via the online GGMN Portal.
- Time series analysis can be performed for each point measurement location to better understand temporal changes of groundwater levels. The time series analysis is a step-by-step procedure to identify trends, periodic fluctuations and autoregressive model. Time series analysis helps defining optimal monitoring frequencies, one of the key components of groundwater monitoring network design.

Moreover, the produced documentation, manuals, and material by UNESCO IHP in the field of monitoring networks have been adopted at national level by many countries, e.g., the New Zealand's IHP National Committee has implemented the UNESCO IHP guidelines in order to benchmark its hydrological activities with those of the rest of the world and in particular introducing data telemetry [69].

3.3. GIS on water resources

The use of GIS is an integral part of programs related with the management of spatial information, such as water bodies, aquifers, and wetlands. Among UNESCO-IHP's activities on coastal aquifers, groundwater-related wetlands in the Mediterranean region, under the GEF/UNEP-MAP Strategic Partnership for the Mediterranean Sea Large Marine Ecosystem (MedPartnership) project, were the creation of detailed digital maps with the use of GIS, **Figure 1**, demonstrating the aforementioned water bodies and wetlands in the specific region [70].

For the creation of the specific map, apart from the data and descriptive information received by the project partners that indicates the characteristics of the coastal aquifers and wetlands, digital data about the groundwater resources and recharge were retrieved by the World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP) (https://www.whymap.org), where UNESCO IHP has leading role in the joint program consortium. Maps prepared by WHYMAP include the Groundwater resources of the world (2008), River and groundwater basins of the world (2012), Global groundwater vulnerability to floods and droughts (2015), as well as the World karst aquifer map (2017).

3.4. Web-based databases

The publication and dissemination of spatial and descriptive information on the cloud are fostered by geo-referenced Web-based databases. The results of the PERSIANN-CCS project are included in the UNESCO-IHP's Global Network on Water and Development Information in Arid Lands (G-WADI) GeoServer (http://hydis.eng.uci.edu/gwadi/), which provides real-time

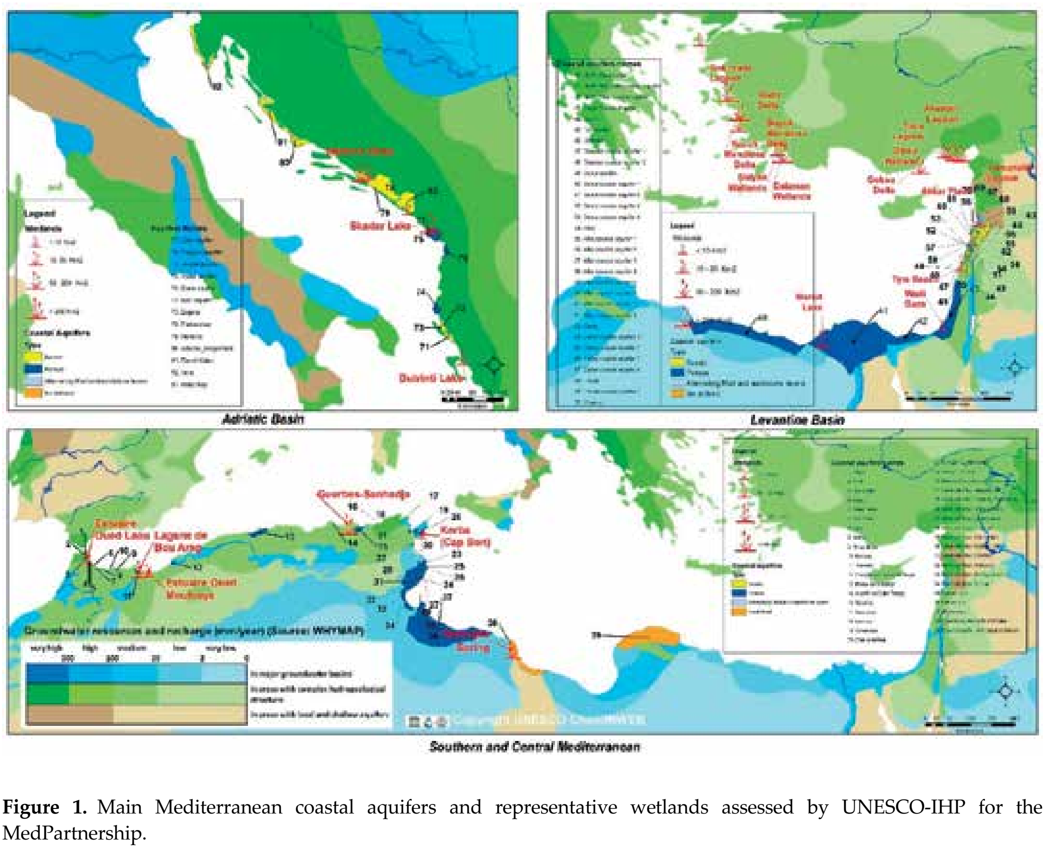

Figure 1. Main Mediterranean coastal aquifers and representative wetlands assessed by UNESCO-IHP for the MedPartnership.

precipitation estimates for water resources managers. By providing updated precipitation observations at the global level, the usefulness of the GeoServer is a direct support to meteorological drought monitoring and early warning worldwide and a contribution to the Global Framework for Climate Services (GFCS) hosted by WMO [71].

Moreover, the UNESCO Chair International Network of Water-Environment Centres for the Balkans (INWEB) has developed, with the use of different technologies, cloud-based databases for the internationally shared aquifers in the SE Europe, North Africa, and in the Middle East. These databases provide dynamic maps where descriptive information and aquifers characteristics can be easily retrieved by the users with the use of the customized Graphical Users Interface (GUI).

The utilization of the Google Fusion Tables Technology by the UNESCO Chair INWEB resulted in the construction of a prototype geo-referenced information system developed for the transboundary aquifers in Africa [59]. The specific information system contains different forms of interactions such as (i) the visualization of an aquifer's spatial extent and projection over the African continent, (ii) the acknowledge of the type of aquifers and the data availability, (iii) downloading capabilities of the data, and (iv) a customized search module that enables the identification of aquifers according to specific criteria, e.g., specific type of aquifers, e.g., porous, with an extent smaller or greater than a specific value and/or where the country population is smaller or greater than a second specific value, and/or where water recharge is more or less than a third specific value. The final output of the search queries is directly linked to the overlaid layers, i.e., only the aquifers which fulfill the search criteria are shown on the map.

The knowledge gained by the aforementioned geo-information system was used in the UNESCO-IHP's activities on coastal groundwater-related wetlands in the Mediterranean region, under the MedPartnership project (http://www.inweb.gr/fusion/coastal_wetlands/coastal_wetlands.html), **Figure 2**. In particular, after the population of a Web database with the 82 coastal aquifers and the 26 wetlands characteristics, JavaScript and HTML5 Web programming languages were used for the creation of the platform interface and the linkage with the database. The final output aimed at (i) facilitating water users to easily retrieve data (spatial and descriptive) related to the coastal wetlands in the Mediterranean, (ii) informing users for the relation of coastal wetlands with underlayed coastal aquifers, (iii) supporting public participation by allowing users to provide comments (either general comments or comments related to a specific geolocation) on the water bodies and environmental areas that appear on the base map, and (iv) enhancing communication by automatically generate emails to specific workgroups whenever comments are made.

As a result of the GEF-funded Transboundary Waters Assessment Programme (TWAP) project, UNESCO-IHP and IGRAC executed an assessment of 199 transboundary aquifers and 43 Small Island Developing States (SIDS) groundwater systems. The data include indicators describing the hydrogeological, environmental, socioeconomic and governance dimensions of tranboundary aquifers and SIDS groundwater systems and are available on IGRAC's Global Groundwater Information System (GGIS) (https://www.un-igrac.org/global-groundwater--information-system-ggis).

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Figure 2. Illustration of the geo-referenced information system and its functionality tolls for coastal groundwater related wetlands in the Mediterranean basin.

UNESCO-IHP is highly involved in the promotion of ICTs tool for water resources management. In June 2013, the UNESCO-IHP launched the Hydro free and/or Open-source software Platform for Experts initiative (also known as HOPE: http://www.hope-initiative.net/). The initiative brings together experts from several fields of water resources to engage in capacity building and trainings based on the use of Free and Open Source Software (FOSS) [72]. Indeed, the FOSS provides reliable sustainable basis for scientific decision-making, which is essential for the sound governance of water resources. In that sense, HOPE offers a more integrative, international and solutions-oriented approach, with the aim of linking high-quality focused scientific research to policy-relevant interdisciplinary efforts for global sustainability. Because of its decreased software costs, FOSS contributes to improve access to technologies and more specifically in the developing world. The initiative also intends to stimulate cooperation in research and development and to enhance their dissemination. Furthermore, since education continues to be ever more linked to technologies, it is essential to promote and foster equal access to ICTs in order to improve the quality of education in the water sector. HOPE participates to that achievement by providing trainings on FOSS and e-Learning open solutions toward Inclusive Knowledge Societies. As a result, capacities of youth and young professionals in the water sector are reinforced, making them more fit and facilitating their integration in a constantly evolving environment. In that sense, HOPE encourages linkages between SDG 6[1] and SDG 8[2] with a focus on fostering innovative job creation.

In partnership with 18 universities, centers, and other organizations, UNESCO-IHP is also collaborating on the FREEWAT (FREE and open source tools for WATer resource management: http://www.freewat.eu/) project, a HORIZON 2020 project financed by the EU Commission. FREEWAT is an innovative participatory approach gathering technical staff and relevant stakeholders, including policy and decision makers, in designing scenarios for the proper application of conjunctive water policies [73]. The consortium organized also capacity building workshops and seminars and provided training to 700 participants.

In the framework of the promotion of open-source and free software, UNESCO is coordinating with the Vrije Universiteit Brussel, the OpenWater Symposium. The symposium focuses on sharing experiences newly lead research using open source software and open access tools within the field of water management and hydrology.

UNESCO-IHP is also behind the Water Information Network System (IHP-WINS), which was launched in January 2017 [74]. This online platform (available at: http://ihp-wins.unesco.org/) incorporates GIS data on water resources into a cooperative and open-access participatory database to foster knowledge-sharing and access to information. IHP-WINS is freely made available by UNESCO's IHP to Member States, water stakeholders, and partners with the aim of facilitating access to information and encouraging contributors to share data on water. Thanks to those contributions, the platform benefits from continuous enrichments with spatial data and documents, coming from various sources. A variety of spatial data is shared and accessible on the platform: scale varies from the global to the very local level, information can be quantitative or qualitative, and both raster and vector are available. Additionally, because the platform is open to a variety of contributors, information covers a large array of water-related topics ranging from quality to risk, to gender, etc. Users can combine those layers of information to create maps tailored to their own needs. Transparency and respect of authorship are guaranteed as all information provided benefit from metadata in a standardized format and from a Digital Object Identifier (DOI). This allows for an accurate identification and crediting of any contribution and easy later sharing. Inter-disciplinary collaboration, professional networking, and mentoring are also stimulated through working groups, where users can exchange and provide feedbacks on their ongoing work. This involvement and participation contributes to the building of an online community. By gathering global and inclusive knowledge on water, and facilitating interdisciplinary collaboration, IHP-WINS aims overall at supporting Members States and stakeholders involved in resources management. The platform will also contribute to close the gap between North and South in terms of access to knowledge. The initiative contributes to the follow-up on the monitoring and implementation of the targets of Sustainable Development Goal 6 (SDG 6) and those of other water-related goals.

IHP-WINS offers different spatial information that can be overlaid to create tailored maps. As illustrated at **Figure 3**, which was developed by IGRAC and UNESCO-IHP in 2015, by

[1] Ensure availability and sustainable management of water and sanitation for all.

[2] Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.

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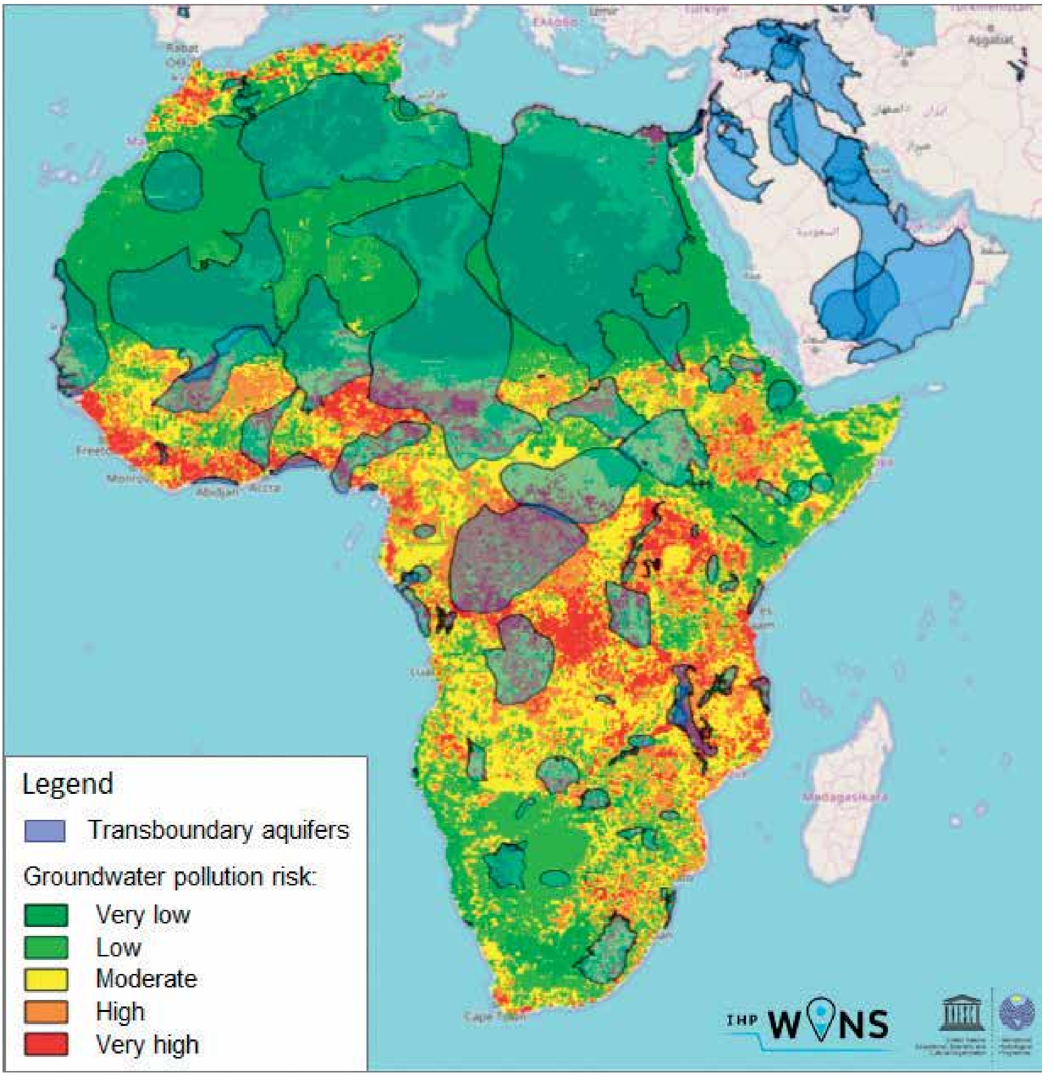

Figure 3. Transboundary aquifers and groundwater pollution risk in Africa.

superimposing information on the spatial extent of transboundary aquifers (1st layer) and groundwater pollution risk (2nd layer), users can quickly identify transboundary resources potentially at risk and the areas where inter-state cooperation for water management should be encouraged.

4. Conclusions

The way in which nowadays information is shared and communication takes place has changed the perspective of our world. The recent revolutionary progress of science, technology, and global communication has put new standards at national and international level, while this progress is also transforming the structure of the economic and social activities. The present work demonstrates that the exponential advances of the information-communication technologies (ICTs) have been also encapsulated in the environmental sector, with special emphasis to be given to the water sector, and international organizations, such as UNESCO-IHP, have adopted this potentiality in their various programs.

The specific work gives also emphasis to the use of ICTs that have been used in different UNESCO IHP programs in order to (i) strengthen the capacity building of water management institutions to implement sustainable forms of utilization, management and protection of transboundary water resources, (ii) facilitate water users to retrieve data related to transboundary water resources, (iii) enable water experts to share data, and (iv) support public participation.

ICTs can also contribute to other thematic fields. A holistic and comprehensive approach to promoting ICT in education, for example, has been conducted by UNESCO [75]. Particularly, UNESCO's Intersectoral Platform emphases on the joint work of the ICTs with science in order to support universal access to education, equity in education, the delivery of quality learning and teaching, teachers' professional development and more efficient education management, governance, and administration.

Integrated environmental data management is concerned with providing an opportunity to draw together relevant data on a transient or permanent basis within the same or across disciplinary boundaries so as to address through analyses, modeling or other means, environmental issues of local, regional, national, or international interest or concern [76]. In the water sector and especially in the integrated water resources management (IWRM), ICTs can provide solutions for its implementation. Particularly, technologies such as satellite earth observation, telemetric monitoring networks, and GIS and Web-based geo-referenced information systems could smooth any differences in the use of technical standards and specifications for data collection and information sharing at national and international level when dealing with transboundary water resources. In the case of engineers, hydrologists, environmental professionals, etc. where emphasis is given on modeling the hydro systems, the aforementioned tools could contribute for a more accurate modeling procedure, since accuracy is subjected to data availability and precision and thereafter for analyzing relationships between physical and ecological variables such as precipitation, river flow, or groundwater recharge [12]. The results of the modeling procedure are useful for understanding how the physical and ecological transboundary systems behave under natural conditions and when anthropogenic pressure is implemented.

However, the proper and standardized utilization of ICTs are a common problem in developing countries. For example, monitoring and early warning systems (MEWS) at operational phase contain the decentralized data collection, scattered over multiple agencies that are dependent on different ministries. This requires collaboration across ministries through a multisectorial approach, which often cannot be effectively implemented without direct support from high-level policymakers [10]. Although most countries have foreseen the development of such monitoring systems in their legislation, it often remains underdeveloped and inappropriate for decision making.

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Communities at the Centre of River Basin Management for Sustainable Development in Northwest Cameroon

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Abstract

Access to a reliable water resource can be a key driver for socio-economic development. Both physical and economic water scarcities are negatively affecting the economies of sub-Saharan African countries, particularly rural communities with the latter considered a crucial challenge. This paper examines the role of local resource users in river basin management for sustainable development in Northwest Cameroon. Using secondary data and empirical evidence collected from three rural districts (Mbengwi, Njinikom, and Ndu) in Northwest Cameroon, it is argued that the involvement and engagement of local resource users and community-based organisations in decision-making processes in river basin management can contribute to sustainable water supplies and enhance sustainable development. In the context of rural communities in the Northwestern part of Cameroon where water supply is mostly through gravity-led techniques, river basins are the main sources of community water supply. It is, therefore, argued in this paper that sustainable development will be possible through a polycentric water governance approach. Thus, clarifying issues of participation, integration, and jurisdiction between the stakeholders (central and local governments and community groups) is crucial for sustainable outcomes. Until the full participation and engagement of local groups and resource users in decision-making processes are achieved, uncertainty will dominate river basin management in Northwest Cameroon.

Keywords: integrated catchment management, community management, water, rural, Cameroon

1. Introduction

Access to reliable clean water is crucial for healthy human communities. The availability of freshwater is a decisive factor in efforts to ensure food production, energy security, and poverty alleviation [1]. However, Africa's environmental and natural resources (NRs) are experiencing increasing pressures from population growths, increasing demands for food, rising urbanisation, climatic variation, and change [2]. In a bid to effectively manage environmental resources, the responsibility for diverse aspects of NR development, utilisation, and management is shared among several government ministerial departments, private actors, and local governances with inadequate coordination structures [1]. This has resulted in serious degradation in part due to patchy sectoral approaches to their governance [3]. The outcome is often ineffective use and derisory protection of valued NRs.

The central question in this field is how to effectively and efficiently manage river basins[1] for sustainable development. The more specific question this paper asks is how to achieve this goal in a context where top-down and centralised approaches to management exclude rural communities who depend on the natural environment for their well-being. Although this pattern of factors may be unique to this case study, several of them are common around the world, and so the paper has broader significance. Resolving all these issues simultaneously may be unlikely, so the paper argues that priority should be given to finding better ways to involve and engage local communities in decision-making processes and that making the roles of national and local governments clear is crucial for effective management and sustainable development[2] (SD). In other words, the paper explores how different forms of governance might lead to easier water user involvement, resulting in more sustainable river basin management. Unfortunately, changes in human behaviour and the pressure put on the NRs have coincided with significant changes in climatic conditions, further compromising the ability of the natural environment to adequately supply the ecosystem services required for human socio-economic development.

Nyambod and Nazmul [3], writing on water management and poverty alleviation, argue that climate change is projected to worsen recent and impending pressures on water resources (WRs) from rising population and changing land use patterns and increase the incidence and severity of droughts and floods. It has been observed that many sub-Saharan African (SSA) countries are expected to experience the most devastating impacts of these changing climatic conditions due to their geographic location, low incomes, low levels of technological development, fragile institutional capability to adapt to rapid variations in the face of environmental alterations, as well as their greater dependence on climate-sensitive renewable NR sectors such as water, agriculture, and energy [4]. Anyadike [5] argues that SSA countries are predominantly prone to climate variability and change due to the fact that many of them are vulnerable to the increasing desertification of our continent, deteriorating run-off from river basins, impoverishment of soil fertility, reliance on subsistence agriculture and animal husbandry, the

[1]This is the land area between the source and the mouth of a river, including all land that drains into the river and provide many functions and uses to humans, other species and the environment [7].

[2]Sustainable development in the context of this study is development that steadily meets the needs and wants of the populations (constant water supply, conservation the watershed, agricultural practices etc.,) without disregarding the capacity of future generations to meet their own needs.

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high incidence of HIV/AIDS and vector-borne diseases, insufficient government mechanisms, and rapid population growth, factors that have the potential to compromise SD.

Existing research recognises the critical role played by water as the centre of socio-economic development [6]. The design and management in river basins are therefore essential aspects in a country's quest for poverty alleviation and SD [7]. River basins are essential for social, economic, and ecological opportunities. They absorb and channel the run-off from rainfall, which, when sensibly managed, can provide fresh drinking water as well as access to food, hydropower, building materials, medicines, and recreational opportunities. In a situation where a river basin crosses a number of countries and communities, the stability might be at stake especially when ineffectively managed [7]. In most countries and communities, the uncertainty of prevalent property rights for *common pool resources* (*CPRs*), combined with market failures to secure the value of river basin services, threatens the sustainability of NRs. This has resulted in the complexity and uncertainty of river basin management (RBM) threatening the activities in the watershed and the river basin's health [8]. Given these complexities, governments, development experts, and non-governmental organisations (NGOs) have recognised the necessity to preserve and manage freshwater ecosystems at the basin level in a bid to address the socio-economic, ecological, and capacity challenges SSA countries face in managing their NRs [9]. These, it is felt, would strengthen environmental sustainability, growth, and equity and this will be possible in an integrated approach.

In the context of Cameroon, for example, NRs have been formally managed by highly centralised national institutions and this has resulted in the exclusion of rural communities from the role resource management [10]. They further question the effectiveness of top-down approaches in promoting equitable access to NRs as well as meeting the needs of the population especially those communities in close proximity to them. However, there is now a shift in policy rhetoric towards adopting community-based approaches, for example, in water resource and environmental management in Cameroon they argued. This initiative could practically learn from polycentric governance approaches[3], which encourage multiple legitimate centres of decision-making that depend on each other. It is argued that polycentric resource governance seeks to enhance participation by promoting inclusive policymaking from different groups, between and among several centres of authority and scales of governance [11, 12]. This assertion, as observed by Tarko [13], is premised on the basis that the existence of multiple policymaking centres creates conditions for self-governance. However, the success of polycentric water governance will largely depend on the degree of collaboration of the different actors and the changes in the socio-ecological conditions of the community.

Given the difficulties of centralised management systems, in many SSA countries, there is now increased realisation of the importance of good governance as a benchmark for promoting effective and sustainable modes of natural resource management (NRM). A considerable amount of literature has been published on integrated river basin management[4] (IRBM) as a

[3]This is a system of management with multiple policymaking centres with interconnecting prerogative, operating under an over-arching system of norms or rules.

[4]This is a management approach that promotes a less wasteful and more equitable and sustainable use of resources within a basin.

promising approach for managing river basins effectively [7, 14]. It is argued, for example, that IRBM will create an environment in which water users with different interests can unanimously arrive at a consensus on the management of their water resources [7, 6]. This approach to river management has been extensively encouraged as a favourable option for managing WRs, although the debate has been clouded due to the lack of serious alternative options for water resource management (WRM) beyond state control [9]. Moreover, the role of rural communities has been distorted because they are often disregarded from important decision-making processes in NRM. This is also the case when state capacity is weak or local groups linger on the margin of support from the government. It is argued that letting local resource users through community-based organisations (CBOs) conceive their own laws may regulate access to the resource, fostering the inclusion of participants who are reliable and excluding irresponsible individuals [9]. Such rules will, in turn, increase and instil confidence among resource users and the management institutions, which is essential for sustainable outcomes [15].

This paper, therefore, explores how local groups and CBOs can effectively contribute to the management of river basins for SD. This paper also argues that river basins will be efficiently managed if CBOs are involved and engaged in decision-making processes coupled with the support of state-level initiatives. This paper starts with an introduction that describes the scenario of environmental resource management, followed by the research approach that was used in the study. The remaining sections explore the concepts and theories of IRBM and CBOs. Finally, the paper examines the potentials of CBO in river basin management for SD in Northwest Cameroon. The conclusion highlights the need to involve and engage community groups and CBOs in policymaking processes for sustainable outcomes.

2. Methodological approach

This study is based on empirical data that was collected between November 2015 and January 2016 in three rural districts (*Mbengwi, Njinikom*, *and Ndu*) in Northwest Cameroon (**Figure 1**). This was done through a *stratified sampling approach*[5] to illuminate the question under study. From these 3 rural municipalities made up of at least 10 villages each, 2 rural communities were randomly selected using the technique of allocation concealment.[6] This gave a total of six villages, *Tugi, Zang-Tabi, Baicham, Muloin, Njimkang, and Ngarum* (**Figure 1**), that were used for data collection. Data were collected from four groups within the communities: households, CBOs, NGOs, and government ministerial departments responsible for water and NRM. It was purposely decided to select 10 households from each of the 6 communities giving a total of 60 households using a systematic sampling interval of 5. The purpose was to evaluate their

[5]This is a sampling method that involves the division of population/communities into smaller groups known as strata. The main advantage is that it captures key population characteristics in the sample and produces characteristics in the sample that are proportional to the overall population.

[6]This is a randomised procedure of data collection that ensures that the different groups studied have similar attributes and prevents researchers and participants from guessing and thus influencing upcoming group tasks. The results give a fair representation as it is unbiased.

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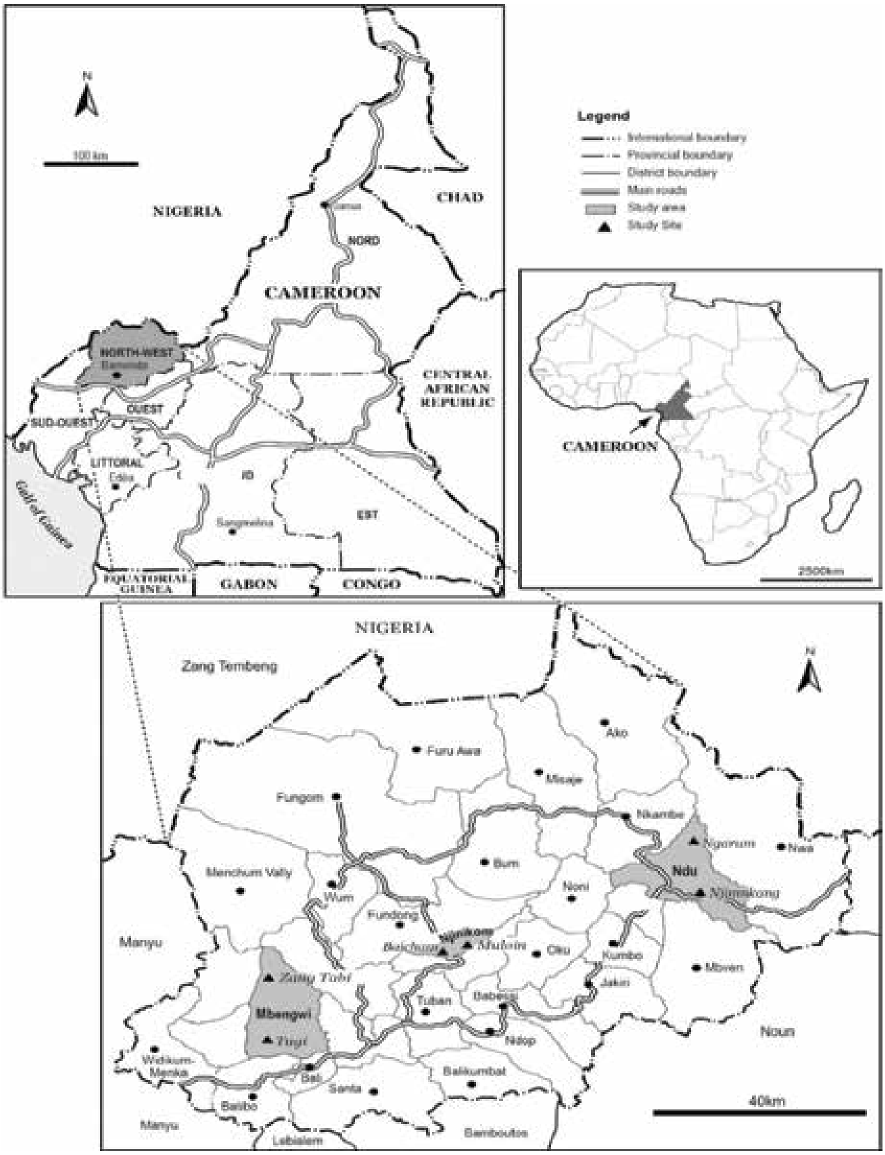

Figure 1. The map of Cameroon and the study sites in Northwest Cameroon. Source: Cartography Unit (2016), School of Geography and Environmental Studies, University of Witwatersrand, South Africa.

participation in community-based management (CBM) initiatives. The first participant in each of the communities was purposely chosen and then the interval of 5 was applied until the required number of 10 was researched.

In-depth interview discussions using semi-structured and open-ended questions were conducted with CBOs, such as informed water and environmental specialists and other stakeholders, from the six villages. Among these include the officials from the Ministry of Energy and Water Resources (MINEE); the Ministry of Environment and Nature Protection (MINENP); the Ministry of Forestry and Wildlife (MINFOF); the Ministry of Agriculture and Rural Development (MINADER); as well as regional departments operating under these ministries in Northwest Cameroon.

Generally, eight officials from different government ministries and four regional officials were interviewed. Interview conversations with the six members of CBOs were also conducted. Discussions with five community leaders were also carried out to understand the role and extent to which community leaders and community members can participate in NRM concerns. This was possible through a snowball technique. This was followed by participants' observation to know the various activities taking place in and around the watershed. The aim of engaging with diverse actors was to assess the institutional, policy and management structures, as well as management practices that exist in the management of the river basins and other NRs in Northwest Cameroon. To complement the empirical data, a review of existing literature on the governance of NRs, polycentric water governance, and CBM using the rapid appraisal technique was conducted.

3. River basin management: a literature review

Water resources are increasingly under pressure from changes in land and water use patterns, combined with the impacts of climate variability and change [4]. This has been caused by rising population, increasing demands for food, and changes in consumption patterns joined with climate change to put enormous pressure on NRs [16]. Furthermore, these resources have been managed from centralised, top-down systems by state bureaucracies disenfranchising local communities from the management process [10]. As a result, international aid organisations, community development experts, NGOs, and local institutions are now looking for a way to effectively and efficiently manage NRs [14]. Development practitioners and social scientists such as economists, anthropologists, sociologists, and political scientists further offer different perspectives on NRM [17, 9, 10]. Pahl-Wostl et al. [18] argue that a universal approach will possibly lead to effective RBM. Regrettably, many current water governance structures in both developing and industrialised countries are unable to address these challenges, and it is often assumed that a "one size fits all" approach could possibly solve the different inclinations among different groups [9]. However, scientific analyses of RBM have shown that they are limited to individual case studies or comparisons between just a few water basins and cannot be generalised [19]. There is, therefore, a need to redefine the procedure for WRM giving more importance to the needs, priorities, and potentials of different stakeholders, communities, countries, and circumstances.

In the context of SSA, NRs were formally managed through indigenous management systems [20]. With the advent of colonisation by Western nations, the indigenous management systems were replaced with technocratic, centralised management models [21]. This system of management as argued by Ostrom [22] and supported by Amungwa [23] excluded rural communities in the management of NRs. It was thought that only a top-down system of management was capable of limiting locals' demand for NRs, which if unchecked through centralised systems would ultimately lead to overexploitation and the damage of the resources [11]. After the independence of most African countries, though, rising number of scientific studies questioned the centralist view of NR governance, revealing that several local user groups have effectively self-governed their NRs [22, 24, 20]. There is now a paradigm shift in the way in which CPRs are governed. Community development experts and policy makers now encourage local users through CBOs and therefore advocate for extensive decentralisation of NRM from central to local institutions [25].

In a variety of NR sectors, developing countries have investigated with shifting NR governance responsibilities down from centralised governments to local institutions, thus stimulating the argument about the role of local participation in NRM. It has been argued that local groups of people have lived with and reaped from their resource systems for ages and have fashioned fairly correct rational patterns of how their biophysical system operates [20]. Tantoh and Simatele [10] are of the view that local groups, through CBOs, are more likely to design adaptable rules for local CPR governance than management approaches developed from the North (see also [20]). Governments are increasingly decentralising the management of NRs from central administrations to regional and to local levels [25]. International aid agencies have frequently advocated decentralisation[7] on the notion that it would bring governance closer to the people and create a range of positive results, including poverty alleviation, ecological sustainability, and SD [17]. Recently, researchers have shown an increased interest in complexity and contradictions of this process, but policy prescriptions and their underlying theoretical models remain overly simplified [26]. Though decentralisation is sometimes represented as a solution for problems of poor NRM, development, and poverty alleviation, the reality is more complex [25]. A number of reforms are being considered as decentralisation, but the results of these reforms are context specific and cannot be universally advocated in every situation [27]. In the forestry sector, for example, decentralisation has been related to better performance but also to ecological degradation, and even when progress in the efficiency of forest management have occurred, matters about fairness persist [28].

Recently, researchers have shown an increased interest in the planning and management of river basins for sustainable outcomes [7]. This is because effective RBM is critical for poverty alleviation and SD, particularly in rural communities in developing countries. It has been argued that the interrelation of diverse water and land uses within a river basin, and their effects on one another calls for integrated management approaches [9]. Faysee [29] is of the opinion that managing a river basin effectively requires the creation of a river basin forum to provide spaces that allow water users and other stakeholders to engage in meaningful dialogue and participate in decision-making processes. This is because different stakeholders have different motivations, needs, and interests and thus a platform that involves representatives of different use sectors (agriculture, domestic use, etc.), as well as upstream and downstream user groups will improve the management of river basins (*coordinated management, conflict resolution, regulation and allocation of water to the different users and uses, etc.*) [30]. This assertion, as argued by [31], is premised on the basis that water platforms provide an

[7]Decentralisation denotes to the delegation of authority from higher to lower level organisations in the administrative ladder, usually from a central government to provincial, regional, district, and sub-district levels.

opportunity for actors with competing interests to meet and seek consensus on issues such as water allocation, negotiation of new rules, and resolution of conflicts. Polycentric forms of governance are clearly set out to consider such a context by establishing a system of rational water distribution and coordination between multiple users and decision makers [19, 12]. Borrini-Feyeraband et al. [20] observe that when NRs are managed at a local scale, for example, rules are needed to resolve disputes between different resource users and communities faster than were previously resolved at higher spatial levels, specifically as ecological conditions change.

In the past two decades, a number of researchers have advanced the concept of polycentric governance, both theoretically and empirically as an effective way to manage river basins [13, 12]. This is evident in the case of Kenya where the drive to polycentric water governance enabled the socio-ecological and institutional interactions through which responsibilities are distributed at the local, regional, and national level and across multiple levels for positive outcomes (*such as regulating water usage and ensuring water availability for downstream users, encouraging local decision-making, and increasing the level of coordination among water users*) [19]. Polycentric water governance as argued by Tarko [13] generates conditions for institutional competition, experimentation, and learning by doing couple with the overlapping of prerogatives that creates the ability to better spread knowledge, provide mutual assistance in cases of emergency, and enhance institutional competition and provide multiple choices to water users without displacing them (see also [17]). In the same vein, Andersson and Ostrom [11] argue that polycentric governance prevents difficulties linked with local tyrannies and inappropriate bias.

Despite the importance and potential of polycentric governance of NRs, many polycentricity scholars argue that results have not always been effective. Orchard and Stringer [12] note that participation is challenging in situations with traditionally top-down and highly ranked institutions, such as Swaziland, where communities and other groups have not traditionally had a substantial input in policymaking. This is indicative of patriarchy. It has also been argued that overlapping jurisdictions in polycentric systems of governance create somewhat redundant institutions [19]. The inability to formulate satisfactory plans to enable and encourage participation of diverse groups within the community from the beginning has restricted the capability of all groups to contribute and share their knowledge during its development [11]. They further argued that procedures for coordination and collaboration between decision centres are crucial features of polycentric regimes.

A stream of recent research has suggested that many policy reforms attempt to restructure contemporary top-down management strategy that often makes the resulting governance structure able to deal with the complexity of resource problems. The principle of IRBM has, therefore, developed to corroborate a framework for coordination, whereby all stakeholders involved in RBM can together develop sensible and satisfactory policies and approaches to watershed management. IRBM, as noted by Mcnally and Tognett [7], has good intentions, aimed at improving monitoring, allocation, and management of WRs. Even though very little has been done to transform theories into practical, components of integrated approaches are evolving in Uganda, for example, where the government has recognised water as a development

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priority and introduced decentralised catchment management plans whilst integrating climate change concerns [32]. An efficient IRBM system will, therefore, require a series of important conditions to be in place such as considerable political will and commitment, meaningful collaboration by several organisations, as well as the existence of national integrated water resource management[8] (IWRM) strategies, water laws and regulation, adequate budget lines, and sufficient technical and human capacity at national and local levels [9].

Mcnally and Tognett [7] are of the opinion that IWRM can be effective in some situations, but this requires substantial cooperation and communication among all interest-driven actors, a dynamic participation of CBOs (farmers, pastoralists, etc.). Faysee [29], for example, argues that transboundary basins cover 71% of the total surface area of West Africa; therefore, many countries have very high dependency ratios. Thus, cooperation among the member state through the Senegal River Basin Development Organization (OMVS) comprising Guinea, Mali, Mauritania, and Senegal will stimulate cooperation between member states and coordinate technical studies and activities to develop and regulate the flow of the river to meet the needs (irrigation, navigation, etc.) of the riparian communities in particular. Also, the Lake Chad Basin Commission (Cameroon, Central African Republic, Chad, Libya, Niger, and Nigeria) has an obligation to effectively and equitably manage the Lake Chad conventional basin and promote the integration and preservation of transboundary peace and security in the basin [33]. However, it is difficult to ensure joint management of a river that spans thousands of kilometres, which is shared among many states. This is because the transboundary nature of the rivers does not easily offer itself to joint management arrangements in which each member state can clearly identify significant benefits than those it can obtain by formulating collaboration arrangements at a smaller scale [33]. For an IRBM to be effective, an enabling environment must be realised. However, the responsibility of the central and local government to the IRBM process is larking [31]. This is because IRBM processes are protracted and time-consuming that often mean IRBM principles are not applied locally [9]. As a result, the extent of IRBM may present substantial technological and institutional difficulties that appear overwhelming for governments and state utilities with limited capacity. Moreover, IRBM processes do not suggest an alternate approach, fit for a more local scale, if these various enabling factors are not present [9]. It can, therefore, be argued that without direct engagement with local groups and CBOs in river basin governance, there is a risk that NRM policies become hypothetical.

In circumstances where the states are considered as unstable and unsupportive, CBM initiatives may be a more realistic and suitable option for engaging local resource users in the management of CPRs [9, 34]. CBM seeks to engage directly with CBOs and the resource user so that they may play an active role in the lifecycle of the project (initiation, realisation, and execution) [15]. The role of CBOs in NRM is a subject that has risen in importance in recent years and it echoes strongly in developing countries where conventional, top-down and prescriptive roles from state bureaucracies for WRM may be unsuitable and many governments are now looking for ways through which they can develop on current management strategies [10]. For many people, CBOs can achieve a vital role in the management of CPRs,

[8]A process that promotes the coordinated management of water, land, and resources connected in order to maximise the socio-economic well-being without jeopardising the sustainability of vital ecosystems

such as water resources and range land. The idea of CBM in RBM is that it offers an opportunity for rural communities to engage in resource management with roles and responsibilities clearly defined alongside those of regulating water authorities. It should, however, be noted that CBM does not attempt to be a direct replacement for national IRBM plans. On the contrary, it provides tangible benefits for CD because it encourages effective use of local resources through monitoring each other's use and in doing so regulating and avoiding misuse [10]. Furthermore, it promotes agencies to engage in hydrological monitoring and to undertake innovative NRM initiatives for sustainable CD [9]. Given the fact that ecosystems are diverse, complex, and uncertain, effective and efficient management of NRs will require considerable capital in obtaining correct data to learn more about patterns of interaction, collaboration, and adapt policies over time that are better fitted to particular systems [20, 35].

4. Water and river basin management in a Cameroonian context

Water is a public good in Cameroon and MINEE is responsible for defining and coordinating the water policies in Cameroon with conventional sectoral approaches in the hands of many ministries and specialised agencies (**Table 1**).

The national policy framework for water in Cameroon follows the 1996 law on the environment[9] (Law No. 96/12) and the 1998 law on water (No 98/005) [2]. These laws are extensions of colonial legislation through which the current management of NRs follows Western models with top-down management approaches. The basis of the 1998 water law in Cameroon pertains to water regimes that are articulated in five headings: (i) the general disposition and the field of application of the code of water, (ii) protection of water resources, (iii) exploitation of water, (iv) conflicts and sanctions, (v) diverse dispositions, and (vi) conclusion. It must be noted that the laws on the environment and water are the cornerstones of the current legislation on water and the water law is intended to complement the law on the environment and thus the principles contained in the law on the environment also apply to water. The water laws in Cameroon, for example, are aligned to some of the prescriptions of the Dublin Principles; fresh water is a finite and vulnerable resource essential to sustain life, development, and the environment, and water development and management should be based on a participatory approach involving users, planners, and policy makers at all levels and water has an economic value in all its competing uses and should be recognised as an economic good. However, the third Dublin Principle (Women play a central role in the provision, management, and safeguarding of water) has not been spelt out in the 1998 water law [36]. Also, the participation of resource users and CBOs appears to be inadequate in accessing data and providing views in public debates. The role of the CBOs is therefore consultative and appears they cannot unilaterally take decisions without consulting local government authorities.

[9]This is a framework law relative to environmental management, juridical framework, elaboration, coordination and financing environmental policies, national environmental plan, environmental impact studies, and protection of respective milieus.

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Organisation	Ministries and Structure	Activities
Executing agencies	Ministry of Environment and Nature Protection (MINEP)	Responsible for the development, planning the management of the environment, and combating pollution and proposes measures for the sustainable management of natural resources.
	Ministry of Water and Energy (MINEE)	Central role in the management and protection of water resources at the institutional level.
	Ministry of Territorial Administration and Decentralisation (MINATD)	Intervenes in the field of water and sanitation through decentralised communities and develops disaster response strategies through the direction of civil protection.
	Ministry of Urban Development and Housing (MINDUH)	Intervenes in sanitation as part of the implementation of the national policy on urban development and housing.
	Ministry of Economy, Planning and Regional Development (MINEPAT)	Responsible for the preparation of general guidelines and development strategies and coordinates the implementation of spatial planning studies.
	Ministry of Domains and Land Affairs	Manages the public and private domains of the state; prepares, implements, and evaluates the land and cadastral policy of the country.
	Ministry of Transport (MINTRANS)	Responsible for the politics of sea transport.
	Ministry of Industry, Mines and Technological Development	Intervenes in environmental problems related to pollution and sanitation inherent in industries.
	Ministry of Finance (MINFI)	Through the direction of the treasury, it intervenes as the Banker of the State for the financing of projects in the Public Investment Budget (BIP).
	Ministry of Agriculture and Rural Development (MINADER)	Responsible for agricultural hydraulics policy in relation to other organisations concerned.
	Ministry of Livestock, Fisheries and Animal Industries (MINEPIA)	Intervenes in the management of water resources through its pastoral hydraulic service.
	Ministry of Economy, Planning and Regional Development (MINEPAT)	Responsible for the preparation of general guidelines and development strategies and coordinates the implementation of spatial planning studies.
	Ministry of Public Health (MINSANTE)	Health surveillance of communities, promotion of environmental health and hygiene, standardisation and regulation of spills in relation to the organisations concerned.
	Ministry of Commerce (MINCOMMERCE)	Responsible for the politics of commercialisation of water resources.
Technical and advisory bodies	National Water Commission (CNE)	It is the steering committee of the project management team for the elaboration of the IWRM plan. It is a consultative body of the government to define and put in place water policy in Cameroon.
	National Environment Committee	Responsible for the impact assessment of development actions on natural resources and to

Organisation	Ministries and Structure	Activities
		raise public awareness for sound environmental management.
Water management & operations organisations	Cameroon Water Utilities Corporation (CAMWATER) & Camerounaise des Eaux (CDE), Energy of Cameroon (ENEO)	CAMWATER/CDE is responsible for the production and commercialisation of the water resource. ENEO supplies hydroelectricity within the country.
Water management & operations organisations	The Urban and Rural Land Development Mission (MAETUR)	Responsible for putting in place water supply and sanitation systems in low-cost housing estates.
	Industrial Zones Development and Management Authority (MAGZI)	Responsible for the creation of industrial zones; these tasks and water and sanitation are limited to the design, construction, and management of secondary structures in industrial areas.
	Cameroon Real Estate Corporation (SIC)	Management of housing areas.
Funding organisations	Ministry of Finance, International aid Organisations, Non-Governmental Organisations	Finance development projects in the domain of water resources.
Research organisations	State universities, higher education institutions with their specialised laboratories, scientific research institutions	These organisations are generally under the supervision of the Ministry of Scientific Research and Innovation and carry out research in the water and sanitation sector.
Non-institutional actors	Non-Governmental Organisations (NGOs) Civil Society Organisations (CSOs), Community Organisations, traditional authorities	They work in the field of water and sanitation. They equally finance projects and provide technical assistance.

Source: [2, 36, 10].

Table 1. National actors involved in water and environmental management in Cameroon.

Cameroon like other developing countries in SSA has as preoccupation to satisfy the population with potable water and sustainably manage the environment with support from the international community. The Cameroon Water Utility Corporation (CAMWATER) and Camerounaise des Eaux (CDE), which took over from the state-owned National Water Company of Cameroon (SNEC) after privatisation, for example, are responsible for providing water supply to urban areas in Cameroon. Given the fact that the current laws have the likelihood of devolving part of the management role of the state to local entities and calls for the participatory approach in management, the supply of potable water to rural communities have been executed by Community-Based Water Management Organisation (CBWMO) with limited financial and technical know-how. This has, however, been enhanced by the Directorate of Water Supply and Hydrology (DWSH) under MINEE that assists rural communities in the realisation of community-based water supply ventures. This is because access to reliable water supply is a major indicator for socio-economic development in Cameroon. This observation, as argued by Fonteh [37] is premised on the basis that the availability of water in sufficient quantity and quality for the protection and promotion of human health; for food, agriculture, and rural livelihoods and well-being; for industrial development; for energy production; and for managing water-related risks is essential for the development and growth of nations. This

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drive has been supported by the laws on the environment and water, which make provisions on sustainable management even though they are poorly implemented.

Regarding RBM, Cameroon has two major and two minor catchment areas. The two major catchments are the Adamawa High Plateau and the Western Highlands, which are collectively referred to as the Cameroon Volcanic Line [38]. The country equally has four drainage basins (*Atlantic, Congo, Benue, and Chad*), all fed by rivers from at least two catchment areas. The major catchment areas from which most rural water supply systems in the North western part of Cameroon are sourced as well as the river courses have been considerably modified from several arrays of land use intensification in the river basins and along river courses. Such alterations have upset the steady pattern of flow of most rivers and this has affected socio-economic activities coupled with the effects of draught and climate change in this part of the country. These changing land use patterns (*deforestation, overgrazing, reforestation, urbanisation, etc.*) have greatly modified the drainage basins over time [38]. In the Western Highlands[10] of Cameroon, for example, massive deforestation for agricultural purposes has contributed to increasing seasonality of streams. However, reforestation using mostly eucalyptus, which is a profitable economic activity in the North western part of Cameroon, is an important factor affecting the flow of the headwaters of major rivers [39]. This is because eucalyptus has a deep rooting system, which can penetrate right to the water table and cause evapotranspiration. This has been described as an environmental terrorism [38]. However, the cutting down of eucalyptus along water courses in many parts of the Western Highlands has resulted in the revival of the regular flow of streams.

It has been argued that climatic change is expected to further increase the stress on WRs in many regions [4]. However, efforts to quantify the economic impact of climate-related changes in WRs are hampered by lack of data [5]. Cameroon through her water laws and texts conceived approaches to halt and reverse the effects of environmental degradation in the context of increased national and international efforts to encourage sustainable and environmental development. In contrast, Fonteh [37] argues that the mastery of the water resource has never been taken as major axes of developmental policy, and despite the existence of different strategic documents of the subsectors of water, a proper National Water Policy (NWP) with objectives and well-defined strategic orientations that clearly outlined management principles do not exist. Critical management problems include insufficient legal and institutional frameworks for the protection and regulation of WRs, inadequate information for informed policymaking, (such as the declining flow of rivers and shrinking water bodies-Lake Chad), and insufficient political will [36]. This affects basic needs, food security, ecosystem degradation, energy production, and water for industries and navigation. There is, therefore, the need to increase the speed for realising an IWRM in Cameroon through the prescriptions from international conventions and international NGOs (*World Summit on Sustainable Development, Global Water Partnership, etc*.). This would assist in the management of river basins (Lake Chad) and reduce environmental degradation. A combination of the different stakeholders is seen as

[10]Comprise the Northwest and Western regions of Cameroon of with much of the higher altitude parts of the region are savannah grasslands used by pastoralists, whilst the valleys at lower altitude are densely farmed or forested.

a potential catalyst for tackling water issues and a way of ensuring that various groups including those traditionally excluded from water development, particularly the youths [40].

5. CBOs and river basin management in Northwest Cameroon

Water management for diverse uses (agriculture, hydro energy production, etc.) at the river basin level has been on the national agenda for decades with the objective to promote water-based socio-economic and environmental management and poverty alleviation in specific river basins of the country. It should be noted that some form of RBM has been in practice in the country and in rural communities where they are the main source of water supply. This is because river basins are the main sources of water supply for domestic consumption and agriculture in Cameroon. Among the four river basins (Atlantic, Congo, Benue, and Chad), two are shared with neighbouring countries (Lake Chad and Congo Basins) [38]. In the past, for example, single-purpose water resource planning was the norm, and surface water quantity was the major concern and rural communities used traditional approaches to regulate the management of their NRs. This system of resource governance was, however, replaced by centralised management techniques that placed resource management in the hands of central bureaucracies, excluding rural communities from accessing these resources for their sustenance. Progressively, contemporary development processes and rising human needs have exerted enormous pressure on the natural environment, resulting in unprecedented levels of environmental degradation. However, CD experts are of the view that the involvement of local groups through CBOs in the management of their NRs could lead to sustainable outcomes [20]. Interview conversations with CD experts in MINADER, for example, show that:

> *"Rural communities have always managed their natural resources for community development. This has been strengthened by technical and managerial support from government departments to ensure sustainable management" (pers. comm, January 2016).*

The above discussion emphasizes the importance of development experts and the role of local institutions in the management of their resources. This is because rural communities have better knowledge of local necessities, have access to information about their environment, are more likely to respond to local needs and wants, and are easily held answerable by local populations [20, 34].

Several studies have documented the effects of the economic crisis that Cameroon experienced in the late 1980s and the Structural Adjustments Programme (SAP) in the early 1990s that reduced government expenditure on some of its traditional responsibilities such as the provision of potable water to rural communities and some other basic amenities [41, 42]. Carmody [43] argues that SAPs did not facilitate recovery, but rather accentuated economic decay because of theoretical flaws in the underlying neo-classical economic model, which misinterpreted Africa's geographic and politico-economic context. This economic downturn was followed by the devaluation of the Franc CFA and the retrenchment of many civil servants leading to hardship and the prevalence of poverty [42]. This increased the exploitation of the

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natural environment. Supporting this assertion, Seghezzo [44] emphasized that people cannot be poor and protect the environment for which they can exploit to improve their living conditions. Given the inability of governments to provide basic amenities to the population, the prevalence of poverty and the increasing pressure exerted by the ever-increasing human needs and wants facilitated the rebirth of self-help and CD initiatives, which were practiced before colonialism. It is within this framework that CBM initiatives through Village Development Associations (VDAs) have been encouraged by national governments, CD experts, and NGOs as one of the ways through which rural communities could take control and manage their resources. Interview discussions with the chairs of the Zang-Tabi Water Management Committees (WMCs) revealed that:

> *"The village development association determine projects that are mostly needed by the community and potable water supply happens to be one of such projects. Residents are thus obliged to contribute both in cash and in-kind in the realisation of community water supply systems and manage the water catchments which are the main source of the water systems" (pers. comm, December 2015).*

In the domain of potable water supply, WMCs have been formed to organise, manage, and protect river basins that furnish the water systems (**Figure 2**).

It should be noted that water is supplied to the communities through the gravity-led technique. This has been facilitated by the hilly landscape of Northwest Cameroon. This method of water supply is sustainable, adaptable, and cost-effective. **Figure 2** shows the structure and relations between the stakeholders engaged in WMCs at the local and national level. The initiation of community water projects is done by VDAs. Since water is life for the people and the environment, rural groups are usually very enthusiastic in the CBM initiatives. Before the execution of the project, the municipal council, CD experts, and NGOs assist the community to design a system based on the local environment. They provide technical, institutional, and financial assistance in the realisation of such community water initiatives. For example, rural Northwest Cameroon is mountainous and the gravity-led water supply technique has been greatly encouraged by CD technicians. After the identification of the technique of water supply, a local Board of Water Management is set up to oversee the construction of the water projects. This is followed by the setting up of the WMCs comprising project committee, catchment protection committee, and stand tap/sanitation committee to facilitate the operation of the system. Those elected into these committees are usually nominated by the quarter heads and must be of high moral standings and must have shown interest in CD projects and are subsequently voted by the entire village during annual village development meetings. The WMCs are responsible for collecting water operation and maintenance fees, organising communal labour, and the protecting the water catchments. CBWMOs, therefore, offer a single approach that involves local men and women in designated communities in a joint action to identify, develop, and test new strategies and tools for improving water systems.

Given the fact that water catchments are the sources of community-based water supply systems, the nature of the catchments will determine the sustainability of the water systems. **Table 2** shows the various forms and activities taking place in and around the water catchments, which have an impact on WRs.

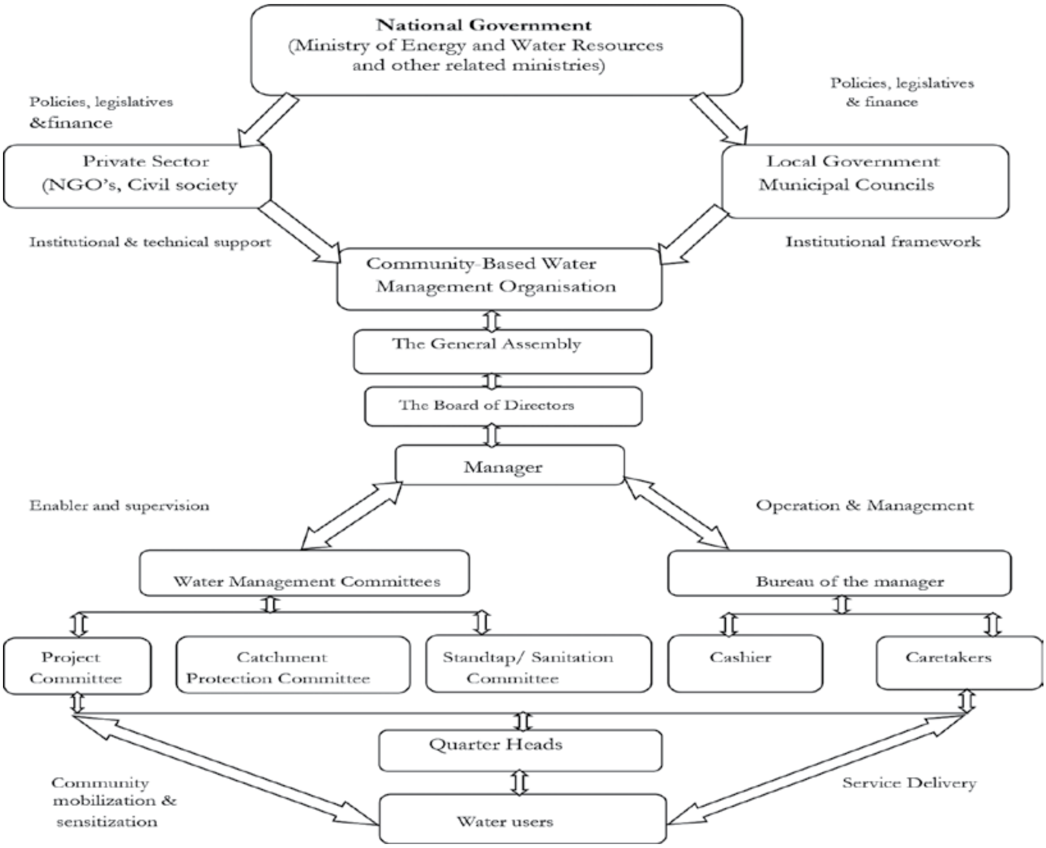

Figure 2. The structure and relationships between local and public actors in water management in rural Northwest Cameroon.

A range of activities take place in and around the catchment. For example, agriculture that is the mainstay of the population occupies 34.4% in Ndu, 34.7% in Njinikom, and 31.8% in Mbengwi. Animal husbandry occupies 45.8% in Ndu, 29.2% in Njinikom, and 25% in Mbengwi, and afforestation with mostly eucalyptus trees make up 39.4% in Ndu, 27.2% in Njinikom, and 33.4% in Mbangwi. The last but not the least is conservatory activities, essential for environmental sustainability, and this makes up 33.3% in Ndu, 33.3% in Njinikom, and 33.3% in Mbengwi (**Table 2**). Building from the activities taking place in and around the water catchments, it can be argued that all the catchments are poorly managed coupled with the effects of climate change with adverse effects on WRs. If an effective water supply is to be assured, the activities in and around the perimeters of the river basins have to be aptly monitored and managed.

Over time, it became clear that concerns relating to both water quality and quantity, and to groundwater and surface water, should be treated together. A more comprehensive approach to planning and management became known as IWRM. Given the fact that the river basins are the sources of water supply within the communities, the water catchment committees make sure these sources are protected against bushfires and animal encroachment. Furthermore, the growth of eucalyptus trees, which is an economic activity within the communities and thrives

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Rural districts	Village	No of watersheds	Nature of the catchments							
			Agriculture		Grazing		Afforestation (*eucalyptus trees*)		Conservation (*bush fires, encroachment)*	
			Frequency N = 38	%	Frequency N = 24	%	Frequency N = 33	%	Frequency N = 15	%
Ndu	Ngarum	2	6	15.9	6	25	7	21.2	3	20
	Njimkang	2	7	18.4	5	20.8	6	18.2	2	13.33
Njinikom	Baicham	2	6	15.9	4	16.7	5	15.2	2	13.33
	Muloin	3	7	18.4	3	12.5	4	12	3	20
Mbengwi	Tugi	2	6	15.9	3	12.5	5	15.2	2	13.33
	Zang-Tabi	2	6	15.9	3	12.5	6	18.2	3	20
Total				100		100		100		100

Source: Field work 2016.

Table 2. Household perception regarding the nature of water catchments in Northwest Cameroon.

well around water catchments, has been a major problem [39]. The effects of climatic change have equally been serious especially on river catchments where agriculture and animal husbandry thrive best. This has been exacerbated by rising population, increasing demands for food, and changes in consumption patterns leading to the encroachment of sensitive regions such as water catchments. In view of these challenges, an IRBM approach through a polycentric system of governance whereby all the stakeholders set up different centres of decision-making bodies and the different levels and scales of management is crucial: for example, bringing upstream and downstream users together, farmers, animal grazers, and other interest-driven actors to a platform to discuss and look for sustainable solutions for sustainable socio-economic development. The aim of IRBM is to ensure multifunctional use of a river and its basin for SD.

6. Conclusions

Governance organisations are imperfect responses to the challenge of collective-action problems. Since these imperfections may exist at any level of governance, this paper argues that the involvement and engagement of local groups and resource users in river basin engagement will instil a sense of belonging and proprietorship. The role of local institutions in NRM is a subject that has risen in eminence lately and it echoes powerfully in developing countries in general and SSA countries in particular where conventional approaches for NRM may be inappropriate and many governments are seeking ways in which to improve on current management and governance strategies. The ecosystem approach promotes the integrated management of land and water and connecting resources in a way that achieves mutually compatible conservation and sustainable use and delivers equitable benefits for people and the environment. This approach strengthens the links between physical, ecological, social, and economic systems to ensure that environmental and economic needs are met and enhanced for long-term purposes [45]. For this to be effective, sustained, water resource policies must mesh with overall national economic policy and related national sectoral policies. Thus, a well-tailored water legislation will create a framework for such integrated management that determines the manner that socio-economic dynamics relate to WRs, providing the context for private, public, community, and individual water activities [46]. An inclusive water legislation *(involving and engaging local groups in decision-making processes)* especially provides a structure for both conservation and SD targets and can spur efficient options in water protection. It should be noted that policies, legislation, the establishment of governing bodies at various levels, and knowledge management are all part of ensuring that the objectives of IRBM are met. Addressing the growing challenges associated with WRM will require bold and difficult changes to existing institutions and policies governing water resources. The establishment of a proper enabling environment that ensures the rights of users and provides the appropriate level of protection of river basins will go a long way to improve and ensure effective IRBM and SD.

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Chapter 12

Strengths and Weaknesses for Climate Change: Adaptation in Water Governance: A Comparison Across Six European Regions

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Abstract

This chapter comparatively analyses the policy and governance contexts of six European regions that are affected by different hydrological impacts of climate change. The results demonstrate that a major governance strength across regions lies in the organization of management capacities to deal with existing water-related risks. For example, the Dutch context focuses on water safety, Cyprus has a clear policy framework to deal with water scarcity and in the Norwegian city of Bergen, wastewater is well managed. As a consequence of this focus on present-day risks, climate adaptation governance also focuses on historical risks. New or exacerbated risks posed by climate change remain largely untreated, and responsibilities for dealing with climate-related risks remain unspecified, as also becomes clear in the German and Spanish cases. A high degree of governmental fragmentation is identified as another point of weakness. Identified most clearly in the Portuguese case but recognizable in all regional contexts, different subdomains of water management are dealt with under separate policies and are governed by different responsible agencies. Consequently, information about current performance of the water system is scattered and coordinative efforts, which are key to developing adaptation strategies, are hampered.

Keywords: water governance, climate change, regional impacts, adaptation

1. Introduction: adaptation to climate change in water governance

According to the World Economic Forum's Global Risks Assessment, water problems are among the biggest threats that humanity is facing in the coming century [1]. In the list of the United Nations Office for Disaster Risk Reduction (UNISDR) disaster statistics, floods and droughts rank in the top three of most experienced climate-related disasters between 1980 and 2011. As climate change affects both the quality and the availability of water in the water system, the provision of basic water-related public services such as water safety, drinking water and sanitation is increasingly under pressure [2, 3]. There is widespread agreement on the need to adapt to the hydrological impacts of a changing climate [4, 5].

While the importance of adaptation is widely recognized, developing effective adaptation solutions is challenged by the high uncertainty connected to the process and impacts of climate change. In the adaptation literature, the importance of flexible adaptation solutions that can be adjusted to new insights about the (experienced) effects of climate change is increasingly emphasized. Under the header of "adaptive capacity", scholars have called for adaptation solutions that are flexible, increase social capital and enhance learning [6–10].

In search of adaptive climate adaptation solutions, the emphasis has been placed on governance arrangements. The UNISDR's Global Assessment Report of 2015, for example, emphasizes that dealing with the impacts of climate change require more than a governmental and top-down technical approach [11]. While technical solutions are essential, governance practices that provide the legal, financial and administrative capacities to implement adaptation measures and ensure a sufficient amount of stakeholder participation and public accountability to safeguard the legitimacy of adaptation efforts are equally important. For this reason, the European Water Framework Directive (WFD) also calls on Member States to develop "appropriate administrative arrangements" to effectively deal with the impacts of climate change [12].

In this chapter, we build on the insight that adaptation to climate change requires more than developing new technical solutions in water management. Just as much, it involves finding new governance arrangements that allocate sufficient (financial, technical and administrative) resources to implement effective adaptation solutions. In addition, because water extremes (droughts and floods) typically affect a wide array of stakeholders dependent on a good management of the water cycle, governance arrangements need to be integrative to facilitate links between different sectors and levels of governance to enhance learning, and facilitate a sufficient amount of public participation to ensure legitimacy.

A huge challenge for developing adaptive governance arrangements in the water sector lies in the huge variability of hydrological impacts across regions. This chapter comparatively analyses the regional governance contexts of six European regions differently affected by climate change: the city of Badalona (Spain) and Bergen (Norway) where the risk of flash floods and combined sewer overflow (CSO) increases, the Troodos Mountains (Cyprus) and the Lower Tagus basin (Portugal) where droughts deplete fresh water resources for public water supply and irrigation and the Veluwe (the Netherlands) and the Wupper River Basin (Germany) where integrated water resources management is affected. For each region, the chapter analyses governance strengths and weaknesses for adaptation to the hydrological impacts of climate change. Based on a comparative analysis, the chapter identifies common as well as regional-specific governance challenges for adaptation to climate change.

The chapter is structured as follows. Section 2 presents the analytical framework used to analyze governance arrangements for climate change adaptation in the water sector. Section 3 describes the findings for each region. Section 4 comparatively analyses these findings, in order to identify common governance challenges in the conclusion (Section 5).

2. Analytical framework

2.1. Adaptive governance arrangements in the water sector

Climate change has huge impacts of the water cycle, but these impacts vary across regions [9, 13, 14]. Whereas in southern Europe climate change may increase the risk of droughts and threaten the availability of water, in other parts of Europe a surplus of water is most problematic and riverine, coastal and storm floods are feared. Similarly, the challenges in urban areas (limited run-off and drainage capacities leading to floods and combined sewage overflows) are usually very different than the challenges rural areas face (decreasing groundwater tables and deteriorating groundwater quality). While the driver behind these risks is similar (climate change), the regional impacts of climate change vary greatly, affecting different parts of the water system and different water-services dependent on that system [2, 15, 16].

At the same time, water governance arrangements differ substantially from region to region. Regional water governance is the product of a long, historical process where arrangements have been influenced by specific geophysical, sociocultural and political circumstances that characterized the regional context throughout history [7, 17]. The adaptive capacity literature emphasizes the importance of an institutional fit between new climate adaptation measures and institutionalized water governance practice for an effective implementation of adaptation measures in regional contexts [18]. The question whether contemporary water governance arrangements can effectively respond to the impacts of climate change, should thus not only take account of the regional variability of climate change impacts, but also of the varying nature of existing regional governance contexts.

This regional diversification surrounding the impacts of climate change on the water cycle and the performances of governance arrangements in dealing with those impacts makes any assessment of adaptive capacity in water governance a challenging task. The adaptive capacity literature therefore displays a strong focus on case studies [19, 20]. And while frameworks have been forwarded to assess or score the adaptive capacity of (water) governance institutions (e.g. [8, 19, 21–25]), these assessment frameworks often remain generalist in scope; they specify general criteria for adaptive capacity but often do not take full account of differences in regional demands and performances.

This chapter uses the three layer framework (TLF) for water governance as a tailor-made analytical tool for analyzing the adaptive capacity of regional water governance arrangements. Rather than formulating criteria, this framework distinguishes between three governance "layers" in which adaptation to climate change takes shape: a content, an institutional and a relational layer. These layers provide a structure to analyze governance arrangements for adaptation to climate change in the water sector, without specifying criteria for adaptive capacity a priori. The next paragraph introduces this framework in more detail.

2.2. The three layer framework (TLF) for water governance

The three layer framework (TLF) for water governance, designed by Havekes et al. [26], builds on the governance gaps identified by the Organization for Economic Cooperation and Development (OECD) in its 2011 study on water governance in OECD countries [27]. In this report, the OECD argues that water governance increasingly becomes a decentralized policy responsibility in OECD countries. In this decentralized policy landscape, cooperation between different sectors and across different levels becomes more important to adequately deal with the impacts of climate change. However, in its analysis of water governance in 17 OECD countries, analysts found 7 "governance gaps" that hampered a good coordination between governance levels and policy domains.

The TLF takes the OECD governance gaps as a starting point. It forwards a structure to think about closing these governance gaps with the building blocks for good water governance specified by the Dutch Water Governance Centre. These building blocks include a powerful administrative organization in water management, a clear legal framework for water management, an adequate financing system, a systematic (planning) approach and a sufficient participation of stakeholders. In the TLF, these building blocks are placed in three different layers of water governance (see **Figure 1**).

First, the "content" layer looks into the substance of adaptation policies. Through this layer, adaptation policies are characterized by their degree (are relevant climate-related risks addressed in the policy framework, or do certain risks remain untreated?). In addition, the content layer assesses the available expertise and skills needed to develop relevant adaptation policies in a governance context. In this report, this is further specified in terms of

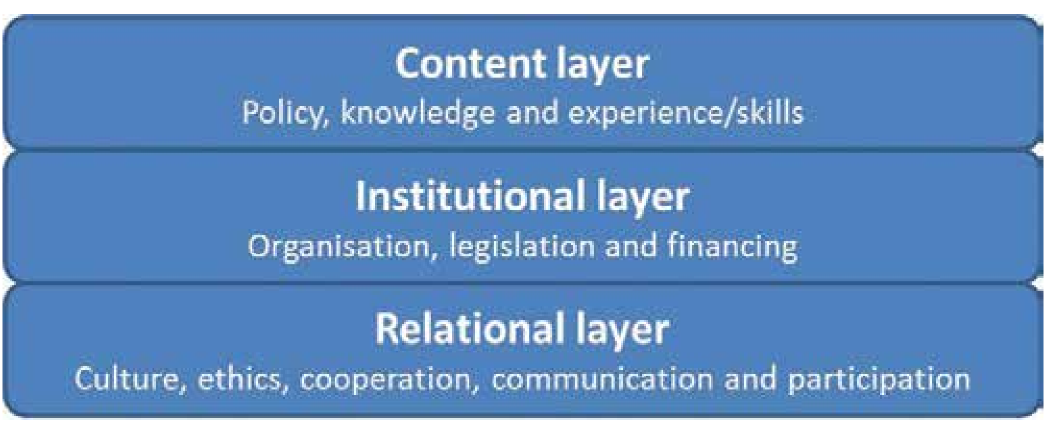

Figure 1. The three layer framework for water governance [26].

information about the regional impacts of climate change and knowledge about possible coping strategies to deal with these regional risks.

Second, the "institutional" layer deals with the organizational aspects that support the effective implementation of designed adaptation policies. In the TLF, good institutional capacities entail clear and legally anchored divisions of responsibility, strong legal and administrative capacities (which, for example, includes workforce, management and supervisory qualities, implementing capacities, monitoring capacities) and a robust financing structure. In this layer, the organization behind adaptation policies is described (e.g., do adaptation policies rely on technical, legal and/or financial policy instruments?).

The third "relational" layer of the framework refers to the requirements placed on the wider governance context of adaptation to climate change. The TLF makes a distinction between culture and ethics, communication and cooperation and participation in this regard. In this report, this is further translated into the extent to which developed adaptation policies establish links between different sectors, the extent to which adaptation governance is clear and open to the public, and the extent to which stakeholder participation is realized in regional governance contexts.

By distinguishing between a content, an institutional and a relational layer, this model helps to better grasp the regional governance challenges posed at the six European research sites: Are challenges mainly related to the content of policy approaches, to institutional arrangements in the water sector or to the relationships and values that underpin water governance? Looking across these regions, this model also contributes to a better understanding of shared governance challenges for adaptation to climate change in the water sector in Europe, as well as of the challenges connected to the governance of certain types of water-related risks.

2.3. Methods

This chapter applies the TLF to analyze the policy and governance context in six European regions: Badalona city in Spain, Bergen city in Norway, nature area the Veluwe in the Netherlands, the Troodos Mountains in Cyprus, the Wupper River Basin in Germany and the lower Tagus basin in Portugal. In each of these regions, climate change poses different risks. Some areas will experience more (storm) floods, in other areas sewage overflow poses a major problem whereas particularly the southern regions face reductions in the quantity and quality of water.

Data for this analysis were collected in two steps. First, questionnaires on policy and governance were sent out to stakeholders; the replies provide information on the policy and governance context at the six BINGO research sites. This allowed to identify site-specific policy and governance needs for adaptation to climate change in different sectors that are impacted by climate change. In **Table 1**, an overview is given of the number of questionnaires collected per research site.

Second, two in-depth expert-interviews were conducted at each research site to generate insights into the national-level policy and governance context that influences regional adaptation. The expert-interviews were held with (1) a key policymaker and (2) a key scientist working on national adaptation policy in the six countries. **Table 2** lists the organizations interviewed at each site.

BINGO research site	Number of questionnaires	Sectors involved
Cyprus/Troodos Mountains region	6	Public administration, public water supply, agriculture, waste water.
Portugal/lower Tagus transboundary river basin	10	Public administration, public water supply, agriculture, waste water, research.
The Netherlands/the Veluwe	6	Public administration, public water supply, water resources management, spatial planning.
Germany/Wupper River Basin	11	Public administration, water resources management, public utilities (water supply and treatment, energy).
Norway/Bergen city	5	Public water supply, research.
Spain/Badalona city	9	Public administration, public water supply, waste water, spatial planning, beach management, research.

Table 1. Questionnaires per research site.

BINGO research site	Expert-interview 1	Expert-interview 2
Cyprus/Troodos Mountains region	Water Development Department	Institute of Environment and Sustainable Development
Portugal/ lower Tagus transboundary river basin (I)	University of Coimbra, Centre for Social Studies (CES)	Tagus River Basin District Administration Division
Portugal/ lower Tagus transboundary river basin (II)	Institute for Water (INAG)	Portuguese Regulatory Authority on Water and Waste Services (ERSAR)
The Netherlands/the Veluwe	Public Administration and Policy department of Wageningen University & Research	Ministry of Infrastructure and the Environment
Germany/Wupper River Basin	North Rhine-Westphalia State Agency for Nature, Environment and Consumer Protection (LANUV)	Wupperverband – Department of Forestry
Norway/Bergen city	Regional Climate & Climate Services and Climate Dynamics departments of Uni Research,	Norwegian Environmental Agency
Spain/Badalona city	Institute of Science and Environmental Technologies (ICTA) of the Autonomous University of Barcelona (AUB)	Spanish Office of Climate Change (OECC) of the Spanish Ministry of Agriculture, Fishing, Food and Environment (MAPAMA)

Table 2. Expert-interviews per research site.

Both the questionnaires and the interview reports were translated by the local project partners in BINGO, and complemented with a first analysis of the meaning of these results in the regional governance contexts. The questionnaires and interviews were further and systematically analyzed in terms of the TLF by the authors of this chapter. The analyses have been sent back to the local project partners for review.

3. Results: governance strengths and weaknesses for adaptation to climate change in six European regions

This section depicts the findings of the analyses of the policy and governance contexts of the six European regions under study for this project. Each subsection starts out with a brief description of the region and the water-related risks brought forward by climate change in the region. This description is followed by an identification of the most important governance strengths and weaknesses for adaptation to the water-related risks. Each subsection ends with a short reflection on the resulting governance needs for effective adaptation to climate change.

3.1. Cyprus, the Troodos Mountains

The Troodos Mountains cover roughly 60% of Cyprus. In the area, most of the island's rivers originate. This research has focused on the downstream area of the Peristerona watershed, which is located on the northern slopes of Troodos Mountains [28]. The three main water uses in the watershed are domestic water supply and irrigation, which rely almost exclusively on groundwater resources [29], and the relatively new sector of wastewater treatment and reuse.

Being a Mediterranean country, water scarcity has posed a persistent risk to Cyprus' water management [30]. The prolongation of dry periods in the future may increase this risk; it may cause groundwater levels to dwindle and existing boreholes to dry out. At present, water availability for domestic water supply just matches the local demand (e.g. in Kato Moni). Besides excacerbating the existing risk of water scarcity, climate change also brings new risks to the region. A deterioration of water quality due to rising temperatures, for instance, poses a new problem. Furthermore, precipitation patterns may change in the near future, with extreme rain events being more likely, which implies higher flooding risks [31, 32].

Governance strengths have been identified in the different layers of the TLF, as regards droughts. Connected to the first layer, water governance in the Peristerona watershed is based on a good understanding of the water system. This is reflected in a strong institutional capacity in the second layer. According to the respondents, regional water governance is guided by a clear and legally embedded policy framework, in which roles and responsibilities for daily management have been defined and divided between different authorities. Furthermore, because key economic sectors, such as agriculture, tourism, environment and energy, depend on continuous water supply, there is strong inter-linkage between these sectors, which supports adaptation in the third layer.

These findings are different for the irrigation subdomain, which operates rather independently from the other policy sectors. Irrigation water supply is managed by local associations of landowners (called "irrigation divisions"), who regulate among themselves the allocation of water resources and share the abstraction costs for irrigation. While administrative and financial resources are less well organized, governance arrangements are characterized by a strong involvement of end-users (land owners), which facilitates the development of tailor-made governance solutions.

Respondents also pointed to a number of weaknesses in water governance. The content of the policy framework is focused on the current situation, and does not sufficiently take into account potential long-term developments such as climate change. At the watershed level, daily management is largely based on empirical knowledge and solutions are based on insights about what works and does not work in practice. As such, adaptation remains focused on existing risks (i.e., frequent droughts) while new risks remain under-addressed. For new or exacerbated risks posed by climate change, it is not specified who is responsible for anticipating the impacts, who is responsible for taking precautionary measures (e.g., who will pay for the infrastructural improvements in the domestic water supply and irrigation networks) and emergency measures (e.g., who is responsible for ensuring the water supply in cases of prolonged drought) and who will carry the burden of potential negative consequences (e.g., higher drinking water prices, crop damages) caused by the impacts. To overcome the potential future risks, and clarify the roles and responsibilities of different actors and end-users in water management, governance arrangements need to be updated and revised.

3.2. Portugal, the lower Tagus transboundary river basin

The research site in Portugal focuses on the lower Tagus transboundary river basin. More than 3 million inhabitants and extensive areas of agriculture are served by its water resources. Water supply, agriculture and hydropower compete for water in a scenario that combines serious riverine and estuarine floods and droughts, and the potential for salt water intrusion from the Tagus estuary.

A governance strength in the lower Tagus transboundary river basin was identified in the Water Law that specifies the roles and responsibilities of different actors at different levels of governance. According to the respondents, roles and responsibilities are clearly defined through this law. For example, water management policies are developed and implemented by the national water authority (the APA) and similar organizations at basin district level.

While water governance in Portugal is backed by a legal framework and delegated to dedicated water agencies, respondents noted a focus on short-term priorities. The existing policy framework is oriented toward pollution control and emergency management, while little structural solutions are developed to deal with long-term quantity and quality decreases. Because of this, critical questions regarding the sustainable, balanced and equitable use of water in the future are not addressed. This concern was reinforced by the trend to outsourcing routine activities, which results in a high dependency on other (mainly academic) entities and limits the national administration's analysis skills.

In addition, the top-down character of water management in Portugal was seen to discourage stakeholders and end-users involvement. Citizens are often only involved in a late stage of the decision-making process, with short time to do so. Moreover, public consultation is generally directed to civil society and not targeted to specific sectors or stakeholders. As a result, awareness of the importance of climate change adaptation is not widespread among different water users and stakeholders.

Respondents also identified a gap between adaptation planning at the national level and the implementation of adaptation solutions in the region. While intersectoral linkages are made at the national level, these links are lost in the translation of national-level objectives to sectoral water management plans at the regional level. This is problematic because sectors can provide constraints for the development of regional water management plans. For instance, improvements in irrigation are constrained by nature policy. Environmental and economic licensing procedures are sometimes conflicting and not well articulated. Links between sectors are very important in overcoming these constraints.

Without an intersectoral approach to climate change adaptation, different sectors have developed their own strategies to climate change adaptation. In the public water supply sector, the Regulatory Authority on Water and Waste Services (ERSAR) offers a number of effective policy instruments, including laws, strategic plans, financial arrangements, knowledge development and public awareness raising campaigns. The public water supply company (EPAL) has independently developed a risk management approach and implemented a set of technical measures to deal with the risk of decreased water quality and quantity.

Adaptation to climate change in the agricultural sector is more complex. Currently, there are public as well as private irrigation schemes, which results in a diversity of water management approaches. Consequently, this sector shows different levels and approaches to climate change adaptation. Despite these differences, respondents note that in general, the agriculture sector has made significant improvements in the products, techniques and technologies used to increase water use efficiency, combat the negative effects of fertilization and control plagues.

To improve adaptation governance in the lower Tagus transboundary river basin, several aspects can be reinforced. Most importantly, national water legislation in Portugal could benefit from simplification and harmonization. There is a good legal framework but there is a need to develop policies, strategies, means and mechanisms to implement measures at the regional level. While especially through sectoral initiatives, water management in Portugal is characterized by a good scientific and technical knowledge base, respondents in particular referred to the absence of a comprehensive policy for water use (in addition to resources management) to balance the claims of different stakeholders on the water resource in lower Tagus transboundary river basin.

3.3. The Netherlands, the Veluwe

The Veluwe is a forest-rich ridge of hills (1250 km^2) in the province of Gelderland in the Netherlands. The Veluwe features many different landscapes, including woodland, heath, some small lakes and Europe's largest sand drifts. Water abstractions provide ca. 2 million people with drinking water and further services industries, agriculture and nature.

The water system is vulnerable to droughts, which previously have led to a ban on overhead irrigation, a deterioration of water quality and insufficient good quality water for humans, nature and agriculture. Increasing droughts will have an effect on vegetation and soil composition, which will in turn influence groundwater replenishments. These effects are not accounted for in current models.

The Netherlands has a strong tradition in water policy. Emerged as a decentralized responsibility, with regional water boards being the oldest democratic institutions in the Netherlands, water management is now a top national priority. Water policy is well institutionalized, with a clear division of responsibilities among different governmental organizations, not only at the national but also at the regional level. The level of knowledge about water systems in general is high, and the Netherlands is leading in water research. Water policy is transparent, with sufficient information available to stakeholders and the public.

There are three main concerns with regard to climate change adaptation at the Veluwe region. Firstly, there is insufficient knowledge about the impact of climate change at the Veluwe and how it will affect stakeholders.

As a consequence, secondly, climate change adaptation is overall not at the forefront of the debate. A National Adaptation Strategy was recently passed by the Dutch parliament but this strategy is not as powerful as the Second Delta Program that specifically deals with water management, as it lacks legislative and regulatory instruments. Despite the encouragement in the EU Climate Adaptation Strategy to develop a holistic vision to adaptation, such a vision is lacking in the Netherlands, which was also noted in an audit by the General Audit Chamber of The Netherlands. Because of this, it is difficult to convince stakeholders of the urgency of climate change adaptation. This makes coordinated efforts difficult, because stakeholders do not see the need disregard their own interest in favor of climate change adaptation.

Thirdly, water policy is, in practice, not very well integrated with other policy fields. Respondents indicate that a vision on the whole water system is lacking. The lacking integration of water policy with spatial planning is also reason for concern. This separation is strongest at the national level. There used to be a coordinated spatial planning in the Netherlands, but that is now more or less abandoned and left to lower levels of government. Instead of a long-term vision for the whole of the country, a more locally oriented problem solving approach is now dominant.

To improve the current situation, climate change research in the Netherlands should be expanded from water management to other sectors such as health care, ICT, and transport to obtain a broader risk assessment. At the national level, this is challenging, since government departments are highly specialized and often have opposing views and interests. At the regional and local level, this should be easier, because the effects of climate change become more tangible. Research such as the BINGO-project could lead to more knowledge and awareness of the impact of climate change at the Veluwe. These impacts can then be addressed as a shared challenge for the stakeholders and allow for more cooperation and coordination. This should be done based on a shared vision of the Veluwe in which different policy areas are integrated. Adaptation should not be incidental, but integrated into the regular operations in the area.

3.4. Germany, the Wupper River basin

The Wupper River Basin is located in the state of North-Rhine Westphalia, Germany, with an area of 813 km^2 and a population of approximately 950,000 inhabitants. The Wupper is an upland river with a length of about 115 km, rising in Marienheide-Börlinghausen (Oberbergischer Kreis district) and flowing into the Rhine River at the city of Leverkusen. The Wupper River and its many tributaries form a river network of ca. 2300 km. The Große Dhünn Reservoir – the second largest drinking water reservoir in Germany – is located within the Dhünn River catchment area, one of the main tributaries of the Wupper River.

The Wupper Association is responsible for water management of all water bodies within the Wupper River Basin. As a public body, the Wupper Association performs its tasks in the public interest and for the benefit of its association members: town councils, local and district authorities, municipal water suppliers, and effluent disposal businesses, trade and industrial organizations in the catchment area of the Wupper River. Their contributions cover the costs of wastewater treatment with sewage sludge disposal, flood protection, managing water flow during dry periods (raising low water levels), water supply provision and maintenance and ecological development of rivers and streams. Close cooperation allows also for the identification of water management strategies. The Wupper Association operates 12 reservoirs, 11 wastewater treatment plants, numerous storm water tanks and flood control reservoirs.

The confidence among the stakeholders to work together on climate change issues stands out as a strong suit for the Wupper region. This is in part because the personal relations and communications are well developed. Water policy in is well integrated with other policy fields, whereas land use planning is mentioned as a successful example. Also, the respondents feel that a wide range of tools is available to tackle current climate risks, such as floods. The professionals who deal with these issues have the right knowledge, skills and training to do so. In addition, the publication of official flood maps is thought to have actually reduced the stress on affected areas. Transparency is considered another strength. Stakeholders are informed about the regular conferences that are organized on water management and feel up to date about new problems and developments in this field.

However, the Wupper region lacks a comprehensive, coordinated strategy to deal with future climate change. Some respondents mention the lack of a general strategy on climate change adaptation, others mention the lack of information exchange among stakeholders with regard to climate change adaptation, though personal relations and communication are well developed. For instance, building owners are insufficiently informed about their risks. This might be caused by a lack of knowledge about future climate change effects on the Wupper Basin whereas respondents point out that more reliable predictions of extreme weather events are missing. This also makes it hard to work on climate adaptation. Finally, the duration (2–5 years) and bureaucratic nature of the planning process is mentioned as a weakness.

The Wupper catchment area would benefit from a systematic inclusion of climate change adaptation in all layers of governance. For the content layer this means developing a general, coordinated strategy on climate change adaptation. This requires more specific knowledge about the future state of the climate in the Wupper Basin and the effects that it has on the different stakeholders (institutional layer). This knowledge then has to be implemented in mandatory guidelines (for instance, for urban planning) and clear strategic goals, including responsibilities, action plans and time lines. Also, respondents suggest to introduce a financing scheme (through fees) specifically to finance climate adaptation.

For the relational layer, the primary improvement would be the coordination of climate change adaptation among different stakeholders and different levels of government. This could be done by expanding the integrated planning approach for climate change adaptation, create better networks and comprehensively institutionalize the collaboration on climate change adaptation. One suggestion is to appoint a climate change officer to coordinate climate change-related activities among the stakeholders.

3.5. Norway, Bergen city

Bergen is Norway's second largest city with 270,000 inhabitants. The city is located on the shadow of the mountain Løvstakken. Currently, the lower lying parts of the city, close to the sea, are going through a big transition where industrial areas are replaced by residential areas.

Known for its rainy climate, heavy precipitation loads pose a major threat to Bergen city. With a closed water system, the city is at risk of flash floods. In addition, because the sewer and stormwater system are not fully separated, there is a risk of CSO. The discharge of CSO's into the subjacent fjord Puddefjorden may cause risks to the health of people living close to the fjord and the environment that surrounds it. These risks can be exacerbated by more extreme weather conditions and sea level rise.

Key strengths of the Bergen governance context for adaptation lie first of all in the content layer of water governance. Information on water-related risks is well organized and much effort has been put in disseminating this information to local governance levels where the main responsibilities for water management are allocated. Second, in the institutional layer, responsibilities for water management are well-arranged, with general guidelines specified at the national level to ensure a basic quality, which can be tailored to local-level characteristics and needs by county and municipal governments. Third, in the relational layer of water governance, strong links have been created between water management and spatial planning.

Key weaknesses of the Bergen policy and governance context are threefold. First, the information on weather-related risks is based on historical data recordings. Less is known about the future conditions, and the threats these conditions pose on (the different regions in) Norway. Second, information that is available is not translated in the existing policy framework on water management. While information on climate-related impacts is increasingly collected and analyzed, this information is not linked to binding actions in official policy documents and laws on water management in Norway. Up to now, climate change adaptation is merely incorporated in strategic plans at all levels (white papers, master plans), but actual responsibilities for adapting to the impacts have not been assigned. Consequently, third, the actual implementation of adaptation solutions is difficult to realize. There is huge regional variation in adaptation governance throughout Norway and because of a lack of enforced implementation, the necessary links between water management and other sectors that are affected by climate change are not made. Because of this, opportunities to develop and implement effective integral solutions for climate change adaptation are currently missed.

In summary, there are three main governance needs (which are linked) to improve the organization of climate change adaptation in Bergen's policy and governance context. First, there is a need for better risk and vulnerability assessments that provide insight into the future risks climate change poses to the water system in Bergen. Second, adaptation policies need to be included in the policy framework on water management, especially for stormwater. While responsibilities for water management are decentralized in Norway, respondents identify a need to take on some responsibility for adaptation at the national level. At the national level, the Norwegian Water Resources and Energy Directorate could include adaptation governance in its guidelines for water management. Also, information about the impacts of climate change could be provided on a less voluntary basis, for example, by requiring communities to take appropriate adaptation measures based on the information they receive. To support such actions, Norway could greatly profit from its decentralized responsibility structure in water governance, where management guidelines are formulated at the national level to ensure equal starting conditions but which can be adapted to local conditions to support the development of effective regional solutions. At the level of Bergen city, respondents recommend to develop a strategic stormwater plan and include it in the municipal master plan.

3.6. Spain, Badalona city

Badalona city is located along Spain's north-eastern coast. It belongs to the province of Barcelona, which lies in the region of Catalonia. Over the years, as the city of Barcelona extended its space claim, this megacity has grown onto Badalona and now it is part of the Barcelona Metropolitan Area. Badalona lies directly adjacent to the Mediterranean Sea, it is bordered by the Besos River in the west and surrounded by the steep Serra de la Marina Mountains in the northeast. The city covers over 21 square km with an altitude difference of almost 500 m running from the mainland down to the sea. It is one of the most densely populated cities in Catalonia with 220,000 inhabitants. Its almost 5 km of Mediterranean beaches offer a popular tourist destination. Together with income from commerce and shipping at the harbor, tourism is an important economic driver of the city.

Characterized by steep differences in altitude (high slopes in the upper parts and flat areas in the lower parts), Badalona is vulnerable to problems with drainage. Urban flash floods and combined sewage overflows (CSO's) already resulted in more than 125 million euros of claimed insurance damage in 1999 and present a major threat to water quality and tourism. Being a seafront city makes Badalona also susceptible to coastal flooding. In 2000, 80 million euros was claimed after a coastal flood. At the same time, the city faces risks related to periods of drought. Its water resources are limited and drought not only challenges the supply of water (scarcity) but also the quality of the water sources. Climate change may increase all these risks in Badalona city.

One of the major strengths of the Badalona governance context is its strong and well-defined policy framework for water management. The policy framework covers all relevant aspects of water management. In each of these subdomains, existing problems are well known and the context is well understood. Policies therefore outline appropriate tasks to deal with these problems. Most respondents also feel that this policy framework is backed by a strong legal and administrative planning structure, with well-defined responsibilities for current water management tasks. In addition, technical knowledge about the current water system is also available to responsible parties. In Badalona, actors are aware of their responsibilities in water management but not always have the resources (financial and technical) to act on this.

A major point of weakness in the Badalona governance context lies in its fragmented structure and incomplete funding, especially for urban drainage system. Responsibilities are clearly defined and assigned, but they are fragmented over different governance levels and actors and there is little oversight or monitoring on the sector as a whole. Because of this, some critical linkages between different subsectors of water management (e.g. sewer and beach management) are currently not made. Furthermore, existing water management practices are underpinned by an incomplete financial structure, because it lacks a municipal sewerage tax and also because financial contributions to water sanitation have been sharply reduced in recent years.

A second major weakness is the focus of current water management practices on the existing situation. There is no structural consideration of the potential future changes and risks instigated by climate change in the governance context. This implies that no responsibilities and resources (financial, administrative and knowledge) are assigned to deal with these future risks, but also that if something goes wrong, no one can be held responsible and parties look at each other to provide a solution.

Both weaknesses may actually reinforce each other. While climate change is a structural factor in national-level policy documents such as the National Hydrological Plan and the National Adaptation Plan, as well as in national-level initiatives such as the set-up of the OECC, these exertions do not easily trickle down to the regional and local level, where governmental fragmentation hinders cross-sectoral collaboration. With little monitoring and oversight, parties will continue to only operate within their limited set of responsibilities and risks that impact on the system as a whole will not be anticipated.

Three governance needs can be identified. First, there is a need for more knowledge about the impacts of climate change on the different subsectors of water management in Badalona and the water system as a whole. This would help to increase awareness about the possible detrimental effects on the water system and help to better anticipate these effects by developing new adaptation policies. Second, there is a need for more coordination in Badalona's water management. This coordination would not only help to create better links between the different subsectors of water management at different levels of governance (city, metropolitan and regional level), but also to establish important links between the water sector and other sectors, such as spatial planning. Third, there is a need for a new governance style that is anticipatory rather than reactive and for policy measures that target long-term developments rather than the existing situation. Increased awareness and better coordination could be the first steps to realize this change, together with the suitable funding framework that nowadays is not enough to cover all the necessities arising from the water cycle management, especially to those related to the urban drainage system.

4. Comparative analysis

What stands out from the analysis is that overall, existing water management practices are well organized at the different research sites. This becomes visible in all layers of the framework for water governance.

In the content layer, the policy and governance arrangements fit the specific contexts of the six BINGO research sites. The frameworks generally cover relevant aspects of water management at these sites (e.g., flood risks, water quality, waste water and beach management). With the exception of some specific subdomains, actors generally feel that existing policies address the most important contemporary issues in water management. In addition, relevant information is collected to support water management in these different subdomains. Responsible actors have access to the information they need to perform their daily management tasks.

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Regional policy frameworks for water management are usually backed by strong institutional arrangements. For the different subsectors of water management, tasks and responsibilities have been clearly outlined and allocated to different actors, at least formally. Overall, administrative resources are also well organized and tailored to these tasks. There is sufficient capacity to implement water management policies, there is sufficient monitoring capacity (e.g., on the price and quality of drinking water), Portugal being the only case where there is substantial concern about monitoring, and in most cases, water management is supported by an adequate financial structure that ensures a long-term and stable source of funding for existing water management practices, but not necessarily climate change adaptation.

Because responsibilities for existing climate risks are well-defined and allocated, water management at the research sites is generally transparent and open to public inquiry. The existing organizations of water management therefore provide for a necessary amount of public accountability. Also, particularly in Germany and in Norway, links between water management and spatial planning are being developed.

It should be noted that for the subdomains of irrigation and groundwater management, policy frameworks seem to be less well organized. In these subdomains, responsibilities are often unclear and sometimes overlap, and a good financial structure is not guaranteed. These subdomains tend to be characterized by a high degree of self-organization, which, on the positive side, has positive effects on the degree of stakeholder participation in these domains.

In addition to these governance strengths for adaptation to climate-related water risks across the six European regions under study, general governance weaknesses can also be identified.

What stood out first from the analysis is that the policy contexts at the research sites insufficiently take future climate risks into account. Existing policies display a clear focus on contemporary challenges in water management. For example, droughts have always been a major problem in Cyprus, thus there are strong policies to deal with water shortages on the island. In the Dutch lowlands, floods and water quantity management have always been the highest priority. Because of this strong focus on present-day challenges, the future risks posed by climate change are insufficiently incorporated in existing policy frameworks. In Bergen city, for example, risks related to storm water are not yet addressed in the municipal policy framework. One of the causes underlying the strong focus on contemporary problems in regional water management connects to a lack of information about the regional impacts of climate change. While different actors are aware of climate change in general, the impacts are only understood on a global level and there is little data on how climate change affects different aspects of the water system in different localities.

As a consequence of the present-day focus in regional water management, climate adaptation policies in the BINGO regions tend to target historical risks. For example, in Cyprus climate change is mostly linked to increasing water scarcity and as a result, existing policies in this field are strengthened to deal with this increased risk. In the Netherlands, climate change adaptation is incorporated under the header of water management, while climate-related water quality and health risks remain untreated. At the same time, it should be noted that these adaptation policies remain highly strategic; the importance of adaptation is particularly emphasized in strategic visions and policy lines at higher levels of governance, but the translation of these visions in actual adaptation policies is difficult in all regions. Because adaptation policies are mainly formulated at a strategic level, clear adaptation targets have not been specified, responsibilities have not been defined, and structural financial resources have not been allocated to address new risks of climate change adaptation.

Another governance weakness is the high degree of fragmentation that characterizes existing water management practices in the regional governance contexts. At the six research sites, different subdomains of water management are governed by different actors and through a different subset of policies. In Cyprus, Spain and Portugal, drinking water, irrigation, waste water and flood risk management are, for example, dealt with under separate policies and by different responsible agencies. Because of this, information about the water system and its current performances is also scattered across different subdomains of water management. This hampers the coordinative capacities of the management system.

A related weakness lies in the lack of collaboration, not only between the different subdomains of water management but also between water management and other sectors such as spatial planning, environmental management, agriculture and tourism. In some regional governance contexts, links with other sectors (mainly spatial planning) have been established, but in general, linkages could be improved. Also, a lack of stakeholder participation was identified. While the structural integration of stakeholder participation varies across regional governance contexts, overall, but problems were experienced with the involvement of new types of stakeholders in water management, such as end-users or the private sector. It is difficult to organize participation of these new stakeholders because they are often not fully aware of the impacts of climate change on their own operations, and because they often have conflicting interests.

5. Conclusion: common governance challenges for adaptation to climate change in Europe

Assessing governance strengths and weaknesses in for climate change adaptation in six European research sites, three main governance challenges can be identified.

First, a common challenge seems to lie in incorporating new climate change risks in the existing policy and governance framework, and in developing and implementing adaptation measures to deal with these new risks. The specific nature of this challenge varies across research sites. In Badalona, the policy framework is strongly oriented toward the existing problems of droughts, water scarcity and floods but the risk of CSO's is insufficiently recognized. And in Bergen, drinking water and wastewater are well managed, but no policies have been developed to deal with the increased risks posed by storm water. However, the general characteristics of this governance challenge are similar.

This challenge can be addressed by establishing a more anticipatory governance setting, which is able to look beyond contemporary problems in water management to the new risks posed by climate change. To facilitate this change, more information about the specific impacts of climate change at the regional level is needed, which should be disseminated to actors and agencies that are responsible for or work within the water system.

Second, there is a need for a more holistic governance approach. Climate change not only affects water management but a whole range of sectors and actors. Therefore, stakeholders from different sectors need to be involved in the formulation of adaptation solutions. Also, better links should be established between the different subsectors of water management (e.g., storm water and waste water in Bergen, or beach management and water quality management in Badalona) to effectively deal with climate change risks. To establish a more holistic approach, the governmental fragmentation that currently characterizes regional water management should be reduced and regional coordination should be improved to enlarge integrative capacities of water governance.

Third, the effective implementation of adaptation measures should be strengthened. To this end, institutional resources need to be organized for climate change adaptation. Policies should define adaptation targets for the treatment of different risks, and allocate responsibilities and administrative and financial resources accordingly.

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Integrated river basin management is an approach focusing on the development and management of land and water resources in a coordinated manner with the primary aim to ensure society development, which is well balanced from the environmental, economic, and social points of view. It is a complex approach, including all aspects of water resource management (water and aquatic ecosystem protection, disaster management, and water use) and covering a wide range of disciplines (e.g., hydrology, ecology, environmental management, and economy), cross-cutting issues (climate change, data sharing, and stakeholder involvement), and approaches (river basin management plans preparation, water-food-energy-ecosystems nexus assessment, science-policy integration, and transboundary cooperation). This book provides a comprehensive overview of achievements and challenges associated with the implementation of the approach throughout the world.

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