SUSTAINABLE MANAGEMENT OF TRANSBOUNDARY RIVER BASINS IN A CHANGING CLIMATE AND HUMAN-INDUCED INTERVENTIONS UPSTREAM

FURAT AHMED MAHMOOD AL-FARAJ

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SUSTAINABLE MANAGEMENT OF TRANSBOUNDARY RIVER BASINS IN A CHANGING CLIMATE AND HUMAN-INDUCED INTERVENTIONS UPSTREAM

Furat Ahmed Mahmood Al-Faraj

College of Science and Technology

School of Computing, Science and Engineering

Civil Engineering

The University of Salford, Salford, UK

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DECLARATION: LIST OF ORIGINAL PAPERS

The novel approaches and findings of this thesis have been published in eight peer-reviewed journals, which will be referred to in the text as appropriate. The original published papers are listed below.

PAPER 1 Al-Faraj, F., & Scholz, M. (2014a). Assessment of temporal hydrologic anomalies coupled with drought impact for a transboundary river flow regime: The Diyala watershed case study. *Journal of Hydrology, 517*, 64-73.

PAPER 2 Al-Faraj, F., & Scholz, M. (2014b). Impact of upstream anthropogenic river regulation on downstream water availability in transboundary river watersheds. *International Journal of Water Resources Development*. doi: 10.1080/07900627.2014.924395

PAPER 3 Al-Faraj, F., & Scholz, M. (2014c). Incorporation of the flow duration curve method within digital filtering algorithms to estimate the base flow contribution to total runoff. *Water Resources Management*. doi: 10.1007/s11269-014-0816-7

PAPER 4 Al-Faraj, F., Scholz, M., & Tigkas, D. (2014d). Sensitivity of surface runoff to drought and climate change: application for shared river basins. *Water, 6*(10), 3033-3048. It is also published in University of Salford Institutional Repository (USIR). Retrieved from http://usir.salford.ac.uk/id/eprint/32872 on 05 November 2014.

PAPER 5 Al-Faraj, F., Scholz, M., Tigkas, D., & Boni, M. (2014e). Drought indices supporting drought management in transboundary watersheds subject to climate alterations. *Journal of Water Policy*. doi: 10.2166/wp.2014.237.

PAPER 6 Al-Faraj, F., & Scholz, M. Impact of basin-wide dry climate conditions and non-climatic drivers: an isolation approach. *Journal of Water and Climate Change* (in review).

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A collaborated research work outside the PhD thesis was conducted and published in the following peer-reviewed journal:

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Furat A. M. Al-Faraj & Miklas Scholz

ABBREVIATIONS

AEZ	Agro-Ecological Zone
AMC	Antecedent Moisture Condition
B-C	Blaney-Criddle
BFI	Baseflow Index
CBD	Convention on Biological Diversity
CFSR	Climate Forecast System Reanalysis
CMI	Crop Moisture Index
DDS	Diyala Discharge Site
DFDC	Daily Flow Duration Curve
DHS	Derbandikhan Hydrometric Site
DI	Deciles Index
DRM	Drought Risk Management
DTL	Drought Threshold Level
FAO	Food and Agricultural Organization of the United Nations
FBA	Frequency Based Approach
FDC	Flow Duration Curve
GHGs	Greenhouse Gases
GADM	Database of Global Administrative Areas
GCM	Global Climate Model (Global Circulation Model)
GDP	Gross Domestic Product
GLCA	Global Leadership for Climate Action
GWP	Global Water Partnership

HDI	Human Development Index
HEC-DSSVue	Hydrologic Engineering Centre-Data Storage System Visual Utility Engine
HMA	Histogram Matching Approach
IoA	Index of Agreement
IHA	Indicators of Hydrologic Alterations
IMO	Iranian Meteorological Organization
INBO	International Network of Basin Organizations
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
MAE	Mean Absolute Error
ME	Middle East
MENA	Middle East and North Africa
MoAg	Ministry of Agriculture
MoAgWR-KRG	Ministry of Agriculture and Water Resources in Kurdistan-Regional Government of Iraq
MoE	Ministry of Environment
MoMPW	Ministry of Municipalities and Public Works
MoP	Ministry of Planning
MoWR	Ministry of Water Resources
M-K	Mann-Kendall
NCEP	National Centres for Environmental Prediction
NDMC	National Drought Mitigation Centre
NMHS	National Meteorological and Hydrological Services
NOAA	National Oceanic and Atmospheric Administration

NRCS	Natural Resources Conservation Service
PDSI	Palmer Drought Severity Index
PET	Potential Evapotranspiration
PNI	Percent of Normal Index
PNPI	Percent of Normal Precipitation Index
RAI	Rainfall Anomaly Index
RDI	Reconnaissance Drought Index
RMSE	Root Mean Square Error
RVA	Range of Variability Approach
SCS	Soil Conservation Services
SDI	Streamflow Drought Index
SPEI	Standardized Precipitation-Evapotranspiration Index
SPI	Standardized Precipitation Index
SRES	Special Report on Emissions Scenarios
SWH	Swedish Water House
SWSI	Surface Water Supply Index
TIWR	Total Irrigation Water Requirements
TTL	Truncation Threshold Level
Tmax	Maximum Air Temperature
Tmean	Mean Air Temperature
Tmin	Minimum Air Temperature
UNDESA	United Nations Department of Economic & Social Affairs
UNDP	United Nations Development Programme
UNECE	United Nations Economic Commission for Europe

UNEPA	United Nations Environment Programme Agency
UNESCO	United Nations Educational, Scientific and Cultural Organization
UN-WWDR	United Nations World Water development Report
USACE	United States Army Corps of Engineers
USAID	United States Agency of International Development
USDA	United States Department of Agriculture
WMO	World Meteorological Organization

ABSTRACT

Management of transboundary waters, particularly in arid and semi-arid regions, is increasingly becoming more challenging, due to the collective impact of human-induced changes upstream and climate change on a transboundary scale. The present prevalent tendency is that the upstream countries unilaterally endeavour to excessively utilize the transboundary water resources on their territories, which greatly exacerbates the vulnerability of the downstream states and intensifies the combined effect. Climate change challenges transboundary waters' management practices by adding a spectrum of uncertainties. A major challenge ahead is to develop measures for sustainable use of shared water resources. This thesis seeks to develop a coherent technical framework that can support the management of transboundary river basins in a sustainable manner, under the combined impact of upstream development and climate change at basin scale, particularly in arid and semi-arid areas. The Diyala river basin shared between Iraq and Iran has been used as a basin representative of a large number of transboundary basins, where myopic water management is a ruling current trend, droughts are anticipated to intensify, and higher tension is likely to emerge.

The study demonstrates a set of novel approaches, including new findings. Three generic empirical formulas have been proposed to estimate the climatically changed mean annual streamflow, the yearly average artificially altered runoff, and the mean yearly collectively impaired flow. A new methodology has been presented to obtain the foreseeable proportional alteration (%) in the mean annual runoff under various climate change scenarios and anticipated droughts. A generic

approach has been also introduced to determine the temporal variations of the baseflow contribution to the total runoff. Moreover, the study offers a solid statistical method to detect the relative impact of man-made changes upstream, which adversely influence the water availability of the downstream state. The study also approaches the sensitivity of water saving to an array of incremental improvements in irrigation efficiency at the basin level. Finally, a set of mitigation measures of the combined effect of climate change at basin scale and upstream development has been proposed, supporting policy-makers and water managers to sustainably manage the shared water resources.

The outcomes of this thesis have been presented in eight papers published in peer-reviewed journals, indicating the notable contribution to the knowledge of effective management of water resources in a transboundary context.

Results reveal that successive and intense droughts, coupled with construction of a series of storage dams and water withdrawals, in particular for irrigated agriculture in the upstream state, have caused considerable hydrologic changes in the flow regime of the downstream country. Climate change at basin-wide scale and man-made interventions upstream are anticipated to increase security concerns between or among two or more than two riparian states.

The study points out that running the irrigation system in a more efficient manner would contribute to water saving and decrease the need for further water supply development for all sectors. Effective irrigation practices reduce water allocation for irrigated agriculture, reduce the pressure on drainage systems, contribute to water-saving and help control the migration of the rural community to urban centres.

Mismanagement of water resources, lack of coordination between different ministers and other related stakeholders, restricted exchange of data, fragmented authority and limited institutional capacity and structures, and insufficient budgetary resources and financing mechanisms at national and local levels form major constraints on the successful water governance of shared resources as well as on putting adaptation and mitigation measures into practice.

Joint monitoring and premature alert systems and transparent exchange of information offer a number of advantages, including a broader and deeper understanding of the combined impact of climate change in a transboundary context and anthropogenic pressure upstream. Such systems should include flow records, climate data and a range of water-quality parameters, in particular at key sites. A specific-basin's characteristics, including environmental, hydro-meteorological, political, economic, social and cultural circumstances are key factors in prioritization of potential plans and actions.

A set of technical supportive tools has been developed for pro-active plans and preparedness actions to handle climate alterations and lessen their potential consequences on various water users, particularly the agriculture sector. The lack of transboundary cooperation in the management of transboundary water bodies is likely to exacerbate the joint impact. This suggests the importance of establishing a joint management body.

The measurement of vulnerability is crucial in adaptation activity to moderate the intertwined potential adverse impact. Risk and vulnerability mapping analyses and assessment are of principal importance to identify the areas, social communities and sectors, whose vulnerabilities are subject to change in response to physical, socio-economic, political, or institutional settings over time, which merit further investigations and urgent actions due to their high potential risk levels.

CHAPTER ONE: INTRODUCTION

1.1 Background

Sustainable management of transboundary waters has become a serious grand challenge facing water managers and decision-makers, particularly in arid and semi-arid regions where water resources are limited in time and space. The challenge is far more serious for lower riparian countries due to a joint implication of human-induced water abstractions of the upstream states and basin-wide climate change. The imbalance between available water and increasing growth in water demand has exacerbated the rivalry between the upper and lower riparian parties to use the shared water resources.

Some 276 transboundary river basins have been identified worldwide (64 transboundary river basins in Africa, 60 in Asia, 68 in Europe, 46 in North America and 38 in South America). These basins account for about 60% of global freshwater flows and are home for about 40% of the world's population (United Nations World Water development Report [UN-WWDR], 2006; International Network of Basin Organizations-Global Water Partnership [INBO-GWP], 2012; Swedish Water House [SWH], 2012). In addition, approximately 300 transboundary aquifer systems are supporting roughly 2 billion people globally (SWH, 2012).

Twenty of the 276 transboundary river basins are shared by five or more states, accounting for nearly 7.2% of the total, the maximum being 18 countries sharing the Danube river basin (United Nations Economic Commission for Europe [UNECE], 2010; Rieu-Clarke, Moynihan, & Magsig, 2012). The large number of shared water bodies worldwide highlights the importance of managing the transboundary waters in a prudent manner, which would be beneficial for all parties.

A broad spectrum of disparities between or among two or more riparian states such as future national development trend, human resources and institutional capacities, physiographic features, socio-economic attributes, hegemonic position, conflicts of interest, and political orientation represents the challenges to reasonably manage and protect shared water resources at the transboundary scale (Savenije & van der Zaag, 2000; Feng & He, 2009; SWH, 2012; INBO-GWP, 2012). The asymmetry has shaped different responses, priorities and arrangements, hydro-meteorologic monitoring networks, data-processing practices and management strategies (Almássy & Buzás, 1999; UNECE, 2007, 2011b; SWH, 2012; Al-Faraj & Scholz, 2014b). However, the ambivalence and diversity in the plans and actions could foster engaged players from riparian states to open up some opportunities to transform disparities and potential conflicts into active long-term collaboration rules.

Despite the efforts of some riparians to reach a binding agreement on shared water apportionment, the current eminent trend is that the upstream countries unilaterally endeavour to excessively utilize the transboundary waters on their territories (Ahmmad, 2010). The development of upstream human-induced disturbances such as damming, large-scale water withdrawal schemes and inter-basin water transfer systems has unequivocally raised concerns about the potential alterations in flow regime at the downstream states (Rosenberg, McCully, & Pringle, 2000; Vorosmarty & Sahagian, 2000; Magilligan, Nislow, & Graber, 2003; Poff et al., 2007; UNECE, 2010).

Climate change, despite uncertainty about the detail of its impact on water resources, is likely to intensify many of these challenges (Goulden, Conway, & Persechino, 2009; Hall et al., 2012). Miller and Yates (2006) have underlined that it is important to understand how climate change may disturb water resources which riparian neighbours depend on and compete over. The Food and Agriculture Organization (FAO, 2011) has reported that the main arguments of concern are: (a) how much climate change there will be, (b) what the impacts will be, and (c) how best to adapt, or better, mitigate the causes.

The Intergovernmental Panel on Climate Change (IPCC, 2001) pointed out that the anticipated increase in global average temperature by the end of the 21st century falls between 1.4°C and 5.8°C. The World Bank (2009) reported that the Middle East and North Africa region (MENA) will likely encounter a decline in rainfall and runoff between –10% and –25% and between –10% and –40%, respectively, and an increase in evaporation rate between +5% and +20%. However, the FAO (2011) reported that runoff patterns are harder to predict as they are governed by land use as well as uncertain changes in rainfall amounts and patterns.

The IPCC (2007, 2014) has repetitively pointed out that many arid and semi-arid areas (e.g., Mediterranean Basin, western USA, southern Africa, north-east Brazil, southern and eastern Australia) will suffer a decrease in water resources due to climate change. By the mid-21st century, annual average river runoff and water availability are foreseen to decrease by –10% to –30% for some dry regions at mid-latitudes and in the dry tropics, some of which are presently water-stressed areas (IPCC, 2007; Sillmann & Roeckner, 2008). Moreover, Arnell and Chunzhen (2001) and Arnell (2004) have highlighted that drought-prone areas and water stress are expected to increase in some parts of the world and flood risks are expected to rise in others.

The IPCC (2001) has reported that the current knowledge on adaptation to climate change is insufficient and there are serious limitations in existing evaluations of adaptation measures. Ragab and Prudhomme (2002) have pointed out some adaptation measures for arid and semi-arid regions, including conventional solutions, such as developing storage dams and irrigation schemes, inter-basin water transfer tunnels and groundwater resources development and management.

Miller and Yates (2006) have emphasized that delicate assessment of the implications of a wide range of potential climate change scenarios is required to effectively handle possible climate alterations. The UN-Water (2008) and the Global Leadership for Climate Action (GLCA, 2009) have reported that with the urgent need to cope with climate change, new opportunities for collaboration in shaping adaptation approaches would emerge.

Milman et al. (2012) have pointed out that adaptation to climate change in a transboundary river basin is not limited to nation and sub-nation-based capacities, but extends to the level of communication, coordination, and cooperation between riparian parties, so as to take advantage of any benefits that may return from coordinated actions. In the same context, Timmerman and Bernardini (2009) have indicated that adaptation to climate alteration is not an independent concern, but it is a fundamental part of integrated water resources management. It should be treated as a continuous, long-term process to be incorporated into all levels of planning and operation or implementation.

The UNECE (2011a) has underlined that very little is done at the transboundary level in assessing the climate change impact and developing adaptation strategies to cope with the range and depths of anticipated impacts. It also highlighted the need for discussing water and climate change in the transboundary context. Furthermore, the SWH has pointed out that the knowledge on transboundary water management is deficient, fragmented and often case-specific (SWH, 2012).

1.2 Problem statement

Human-induced interventions upstream twinned with the recent subsequent and prolonged drought episodes have markedly exacerbated water resources management challenges at transboundary scale. The collective impact of anthropogenic activities upstream and basin-wide frequent drought incidents have increasingly impaired the resilience of the system and magnifies the vulnerability magnitude of the downstream country.

Knowledge gaps have been observed in the overall risks of the combined impact on the stability of the hydrologic regime and availability of water resources of the lower riparian country. Despite the growing need to consider basin-wide water resources management, the current prevailing trend is a country-based unit management, which reduces the size of the problem and weakens the actions. Moreover, there is a lack of profound understanding on water exploitation, development and the absence of workable adaptation measures to handle and mitigate the mutual impact in the transboundary context. The knowledge gaps have positioned the development of practical adaptation arrangements and mitigation measures in the fore of research work that needs to be urgently initiated. The main question which arises is

"What effective adaptation practices and mitigation measures can be developed and adopted to handle and soften the combined impact of climate change at basin-wide scale and upstream human-induced pressure"?

The size, magnitude and intricacy of the problems facing shared basins make it essential to use a representative example watershed to study the problems and potential solutions. The Diyala (Sīrvān) river basin shared between Iraq and Iran was targeted in this study. The magnitude of problems plaguing the basin is in common with dozens of transboundary watersheds such as Nile, Euphrates, Tigris, Karkheh, Karun, AlWand, Jordan, Shatt El-Arab, Yarmuk, Volta, and Senegal, where the problem of over-exploitation of shared water bodies is expected to exacerbate under the collective impact. Myopic management of the limited water resources contributes to the tensions and is likely to lead to the emergence of disproportionate socio-economic and environmental impacts.

Understanding the basin and how it could respond to development is an immensely complex task, which needs to be carefully treated by all sharing parties. Findings are expected to form prominent and distinctive contributions to the knowledge of the sustainable management of water resources at transboundary level.

The examined watershed occupies a drainage area of about 32,600 km^2, of which 43% spans Iraq and 57% spans Iran. The basin is extensively stressed, densely dammed and agriculturally highly developed, including a complex web of hydraulic structures, irrigation projects, fish farms, distribution systems and municipal and industrial facilities. Some hydraulic facilities and an inter-basin water transfer network are currently under construction and anticipated to be functioning in 2018, while under study or planned hydraulic works are considered medium to long-term period targets.

The basin represents an example of politics of silence, mutual accusations and non-cooperation, which have had been recorded over decades. Absence of a binding water treaty, inability to reach any binding water sharing agreement in the foreseeable future, mismanagement and short-sighted governance of water resources in the lower riparian party, low irrigation efficiency at basin-scale, and lack of information-sharing channels are the main factors impeding the prudent management of transboundary waters. Moreover, data and information are guarded as a state secret.

1.3 Aim and objectives

The overarching aim of this study is to develop a coherent technical framework that can support the management of transboundary river basins in a sustainable manner, under the mutual impact of upstream human-interventions and climate change at basin scale, particularly in arid and semi-arid areas. To achieve the research aim and address the key research gaps, the following objectives are set:

1. Identify and separate the impacts of historical droughts and upstream development on the lower basin flow regime. Estimation of groundwater contribution to total unimpaired runoff.
2. Assess the possible impacts of climate change/future development at the basin level on the lower basin flow paradigm.

3. Assess the sensitivity of irrigation water requirements to a spectrum of improvements in irrigation efficiency at basin scale and lower basin's inter-basin water transfer schemes.
4. Integrate methods into a coherent technical framework that can support decision-making for mitigation to and adaptation with the collective impact.

Figure 1-1 demonstrates the progression through the objectives to deliver the technical support framework.

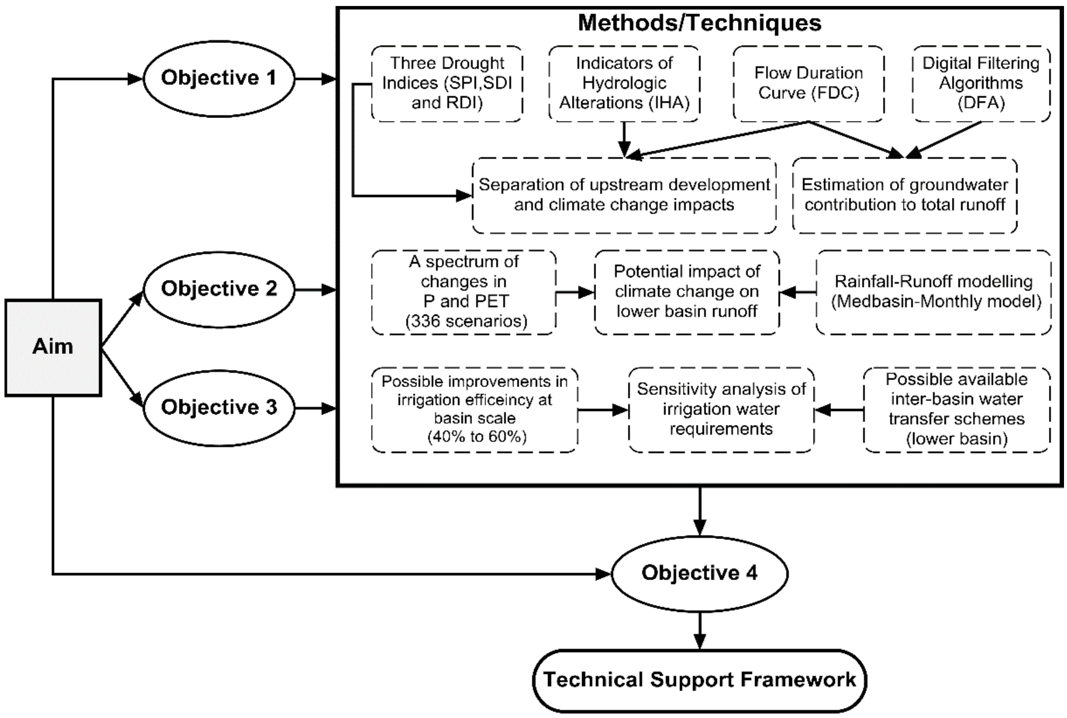

Figure 1-1: The progression through the objectives to deliver the technical support framework

1.4 Importance of the study

Considering the problem statement, it becomes important to address key knowledge gaps with respect to the combined impact on water availability of the downstream countries. The study provides a solid technical framework that can support the management of transboundary river basins in a sustainable manner. Findings will assist community leaders to transcend managing the portion of the basin, which lies within the country boundary to a more appropriate and broader scale of management referring to the transboundary basin level. Moreover, it will support decision makers in making decisions that strengthen resilience to the consequences of the mutual impact.

1.5 Thesis structure

To meet the objectives and achieve the overall aim, and for easy flow, the thesis has been made up of five main chapters as described below:

Chapter one (this chapter) begins with the background context, provides the problem statement and research gaps, defines the study aim and outlines objectives, identifies the importance of the study and lists the thesis chapters.

Chapter two examines the existing literature including but not limited to challenges confronting the plausible management of transboundary waters, climatic and non-climatic drivers, climate change and synthetic scenarios, hydrologic anomalies, and groundwater contributions to total runoff, drought indices, rainfall-runoff modelling, sensitivity of irrigation water requirements and adaptation to climate change in the water sector.

Chapter three explores the materials and methodology in detail. This chapter encompasses the data collection and management and the approaches used to achieve the objectives and the overarching aim. The approaches are offered in several sections corresponding to the defined objectives.

Chapter four introduces the results and discussion. Findings are presented and discussed in detail.

Chapter five provides detailed conclusions and lists recommendations for future work.

CHAPTER TWO: CRITICAL LITERATURE REVIEW

2.1 Management of transboundary waters

2.1.1 Sustainable management and disparities between riparian countries

The sustainable management of competitive use of water resources in transboundary river basins has become a great challenge encountered by the riparian states. The diversity and differences in political attitudes, power asymmetry, socio-economic development, institutional capacity and skilled human resources, geopolitical sovereignty, cross-sectoral coordination and efficiency of physical infrastructure make it hard to achieve a provident joint governance of transboundary waters.

The asymmetry between riparian countries emphasizes the necessity for an inclusive approach for sustainable management and protection of transboundary waters (Swain, 2011). The differences have led to formulating different outlooks, priorities and arrangements, monitoring networks, management plans and practices, and adopting conflicting attitudes over the water (Kundzewicz et al., 2007; Swain, 2011; Al-Faraj & Scholz, 2014b). The asymmetry is a critical element, which may lead to dominance of one party, likely the upstream state, over other riparians. Recent droughts and climate change implications have intensified the challenge, especially for the downstream countries (FAO, 2011; Swain, 2011; Caitlin & Francesco, 2013).

The United Nations Department of Economic and Social Affairs (UNDESA, 2014) reported that issues of transboundary scale predominantly include either the absence of a water treaty that governs water utilization among riparian countries or considerable shortcomings in most of the signed agreements. In the same regard, Brels, Coates and Loures (2008) have stated that despite the increase of formal agreements, there are still numerous watersheds which lack a rational legal framework for coordination and collaboration. Swain (2011) argued that some riparian countries, believe that they have the absolute sovereignty right to fully control and use the part of the transboundary water within their territorial boundaries. The Ministry of Energy of Iran (Ministry of Energy, 2003, p.13) reports that:

“All the waters flowing out and join waters must be harnessed and consumed, and Frontier Rivers must be systematized observing economic and environmental standards”.

The ministry (Ministry of Energy, 2003, p.10) also reported that:

“The projects of transferring water from a watershed to another must be considered from the viewpoint of sustainable development while observing interested parties’ rights and their technical, economic, social feasibility and explanation and national interests meeting various needs”.

Another related issue is that some riparians such as Iraq and Egypt claim that they have the acquired rights to preserve their dominant positions in the allocation of water mainly due to the ancestral irrigation use of the Euphrates and Tigris rivers in Iraq and the Nile river in Egypt (Swain, 2011). These countries will not enjoy guaranteed water supply at past historical quantities.

Marcuello and Lallana (2003), Goulden et al. (2009) and Al-Faraj and Scholz (2014a,b) have highlighted that the flow regime of the lower riparian states is challenged by unilateral land use changes on the upper reaches of the shared watersheds, damming the main watercourse and its tributaries, and climate change.

According to the IPCC (2007) and Arnell and Charlton (2009), four key barriers to cope with environmental change in terms of water quantity and quality have been identified. Firstly, there may be physical barriers that constrain the performance of a particular adaptation measure. Secondly, there could be economic constraints, if some adaptations are considered to be too costly. There may be socio-political barriers to adaptation in the postures of stakeholders to proposed measures; and finally, the capacity of water management institutions could limit the ability to promote or implement adaptation strategies.

Timmerman and Bernardini (2009) have pointed out that the challenges facing the provident management of water resources are not limited to conflicting postures among riparian states. Water conflicts can extend to small political, spatial, and geographical domains such as local governments, local water authorities, and tribal interests, as well as between the federal government and regional governorates. The various beneficiaries act differently, which may lead to conflicts due to diverse values, goals and polices. However, the main challenge which remains is that the transboundary water resources join a group of actors in a multifaceted complex system driven by various disparities.

2.1.2 Integrated Water Resources Management

Shortage and scarcity of water resources continue to be a key challenge, particularly in a water scarce region, mainly due to the adverse impact of climate change, population growth and landscape modifications. These challenges have put the sustainable development of the available water resources, in the forefront of the long-term plans and strategies. Integrated Water Resources management (IWRM) has become a universal accepted approach for attaining sustainable water resources management. Given the difficulties and complexities of managing shared river basins, intertwined with the increasing growth in water demands, a clear identification of the gaps and challenges in transboundary IWRM is essential, with a view to achieving a sustainable management of water resources (UNEP-DHI Centre for Water and Environment, 2011).

The IWRM defined by the Global Water Partnership (GWP) as “a process which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (GWP, 2000,2003; GWP and International Network of Basin Organizations [INBO], 2012).

The European Commission (EC) indicated that IWRM expresses the idea “that water resources should be managed in a holistic way, coordinating and integrating all aspects and functions of water extraction, water control and water-related service delivery so as to bring sustainable and equitable benefit to all those dependent on the resource” (International Water and Sanitation Centre [IRC], 2004).

The United States Agency for International Development **(**USAID) defined IWRM as “a participatory planning and implementation process, based on sound science that brings stakeholders together to determine how to meet society’s long-term needs for water and coastal resources while maintaining essential ecological services and economic benefits”. IWRM helps to protect the world’s environment, foster economic growth and sustainable agricultural development, promote democratic participation in governance, and improve human health" (Cardwell et al., 2006).

The IWRM is an empirical- concept that was resulted and shaped from the on-the-ground accumulated experience of practitioners (UNEP-DHI Centre for Water and Environment, 2009). Equity, efficiency and sustainability are the three key concepts which in one form or another present in all definitions of IWRM (IRC, 2004, UNESCO, 2009). The GWP and INBO (2012) pointed out that IWRM is based on four principles defined and adopted by the international community since the International Conference on Water and the Environment in 1992 (so called the Dublin principles). These principles are: "(a) fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment; (b) water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels; (c) women play a central part in the provision, management and safeguarding of water; and (d) water has an economic value in all its competing uses and should be recognized as an economic good".

Savenije and van der Zaag (2000) indicated that politics, technical cooperation and institutions are the "three pillars" that supporting the sharing and management of international water resources (the roof), while the IWRM represents the foundation of the three pillars (Figure 2-1). The "three pillars" of IWRM according to the GWP (Figure 2-2) are: Enabling Environment, Institutional Framework and Management Instruments (GWP, 2004). Moreover, Savenije and

Van der Zaag (2008) have suggested that IWRM has to take account of water resources, water demand, the spatial scale and the temporal scale.

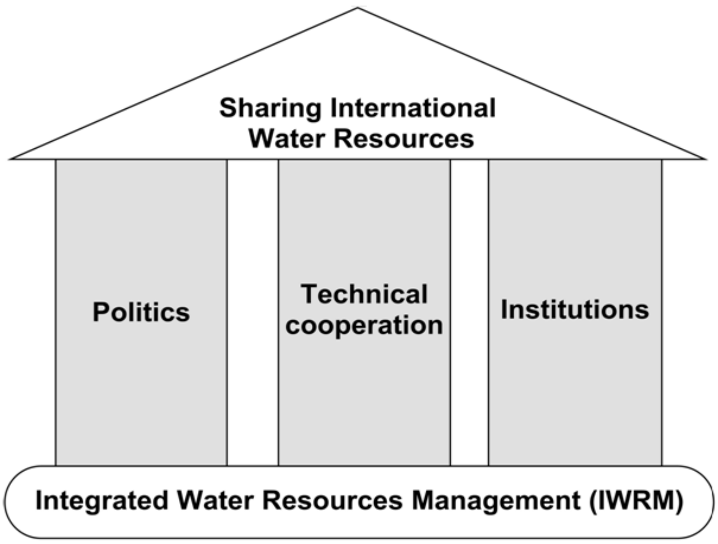

Figure 2-1: A classical temple for sharing international water resources (*After* Savenije and van der Zaag (2000)

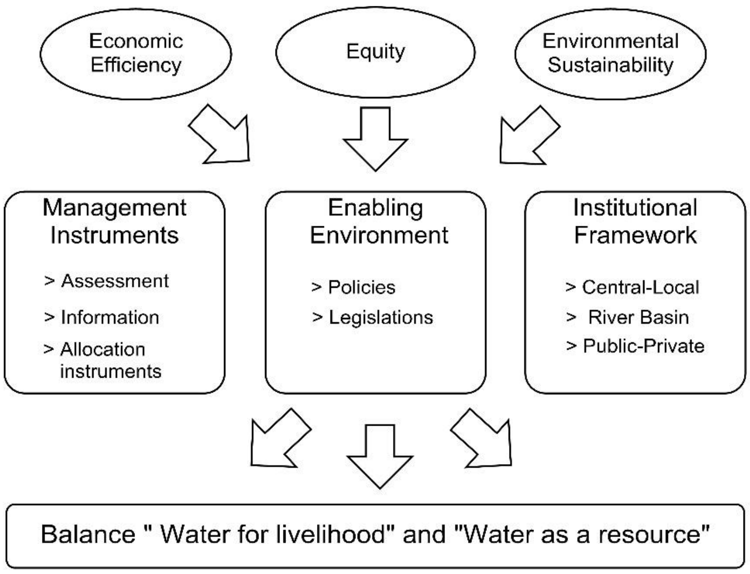

Figure 2-2: The “three pillars” of Integrated Water Resources Management: Enabling Environment, Institutional Framework and Management Instruments (*After* GWP, 2004)

The UNEP-DHI Centre for Water and Environment (2011) underlined that there are five main features for IWRM in transboundary basins. These features are: (a) clear and solid institutional arrangements, regulations, and implementing process; (b) reliable water-related data, clear and firm operating system in the basin-wide context; (c) a complete and consistent basin-wide policies and strategies; (d) a transparent communication between all actors and broad stakeholder involvement in water planning and operating decisions at basin level; and (e) basin sustainability performance indicators and an agreed approach to monitor and report on how the basin is being managed and the resources consumed and protected.

The GWP (GWP, 2003) pointed out that the Collaborative Decision Making (CDM) is a suitable and appropriate mechanism within the framework of IWRM and Integrated River Basin Management (IRBM). The CDM leads to the participation of all parties that are related to water resources management. The CDM defined as "a joint effort among government agencies, private sectors, NGOs, the public, universities and other relevant stakeholders aimed at improving the present management system through increased information exchange among the various parties in the community and improved decision support tools" (Elfithri et al., 2008). Figure 2-3 demonstrates the integration framework between IWRM, IRBM and the CDM (Elfithri et al., 2008)

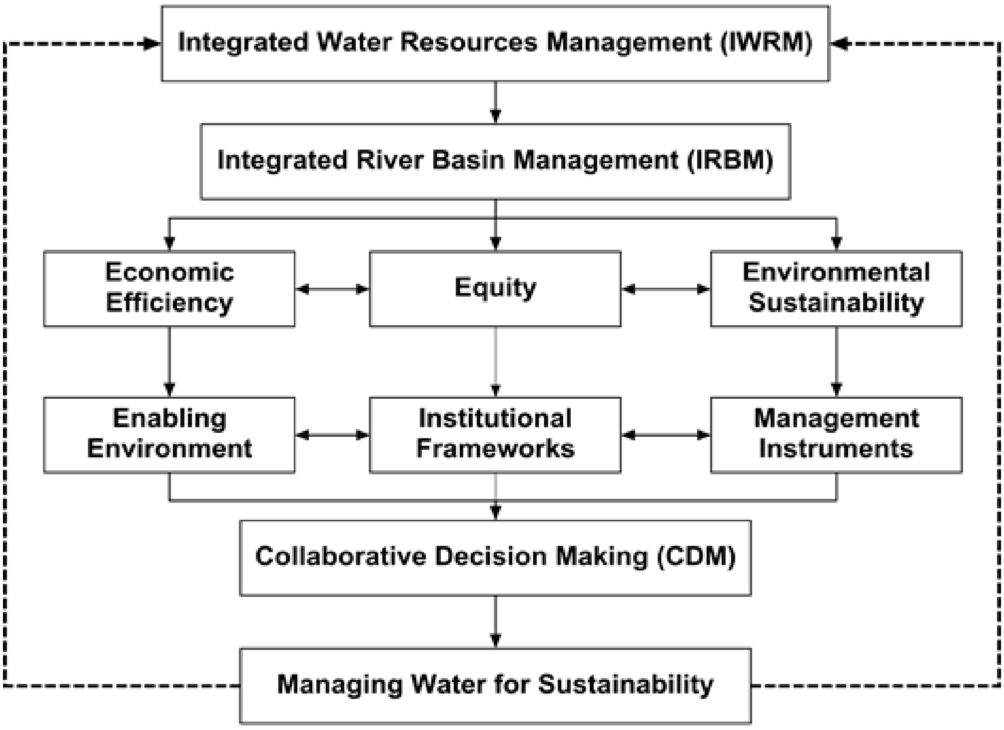

Figure 2-3: Framework of IWRM and IRBM that showed the importance of CDM (*After* Elfithri et al., 2008)

While the principles and concepts of IWRM have been commonly acknowledged at international and national scales, the implementation of IWRM has not adequately progressed in many basins (AWRA, 2011, 2012), partly due to a spectrum of disparities between riparian countries (UNESCO, 2009; (Najjar & Collier, 2011). The systems of governance, legal frameworks, decision-making processes and types and effectiveness of institutions, mostly differ from one country to another, and often in very significant ways. Moreover, the current evidence indicates that irrespective of the current popularity of the concept, its impact to improve water management has been, at best, marginal (Biswas, 2008).

The UN-Water and the GWP (2007) and the UN-Water (2008) pointed out that the supply-side solutions alone are not adequate to address the ever increasing demands from demographic, economic and climatic pressures; waste-water treatment, water recycling and demand management measures are being introduced to counter the challenges of inadequate supply. The IWRM focuses on better allocation of water to different water user groups and the importance of involving all stakeholders in the decision making process. Moreover, is also recognized as a framework for the adaptation of water management to climate change and the management of floods and droughts (UN-Water and GWP, 2007).

The GWP (GWP, 2004) has illustrated the stages in IRWM planning and implementation (Figure 2-4). The process starts with the national goals and continues into the actions for implementation and monitoring and evaluation progress.

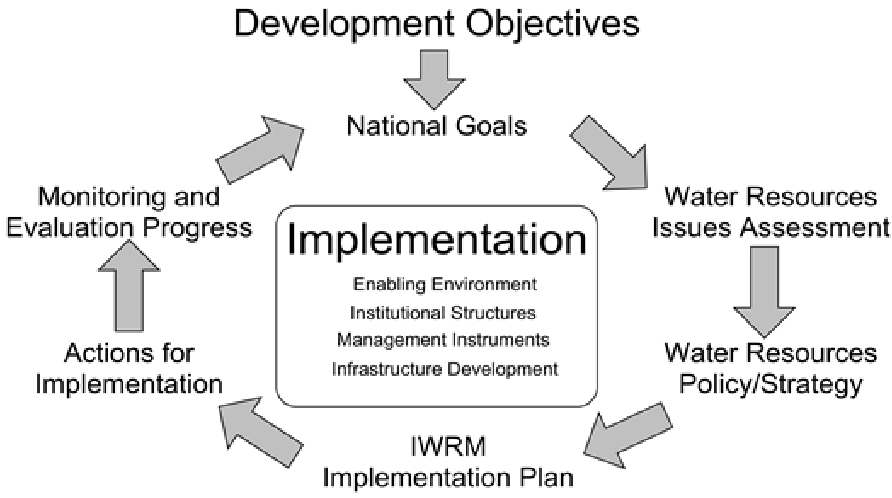

Figure 2-4: Stages in IWRM Planning and Implementation (GWP, 2004)

Hemoh and Shenbei (2014) have developed a sustainable integrated management framework for water resources (SIMFWR) for the available water resources in Africa arid regions based on the review of relevant literature. The proposed framework (Figure 2-5) highlights the foremost actors/stakeholders in an integrated water management system which is labelled along the normal triangle and the components that are essential for successful and sustainable management of water resources in labelled regions of Africa which are also label along the square. The inverted triangle represents the tools for a sustainable water management framework and the circles are considered the technical system for water resources distribution and control pending the adequate assessment of the components and the involvement of all relevant actors.

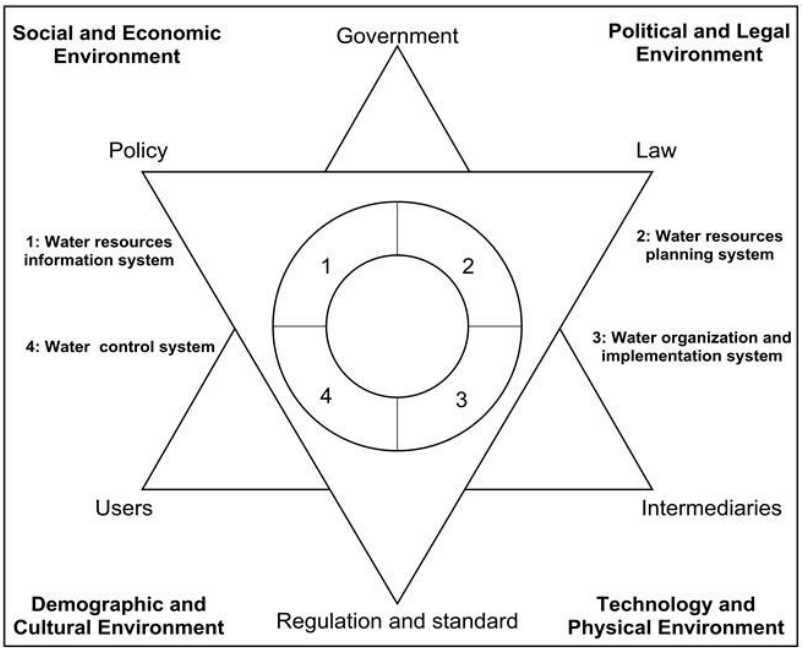

Figure 2-5: Sustainable Integrated Management Framework for Water Resources (*After* Hemoh and Shenbei, 2014)

However, solid and active water governance is essential to efficiently put the IWRM in practice. Political will, coherent legal framework, viable involvement of all water related stakeholders and transparent exchange of data and information are fundamental elements to successfully implement IWRM and achieve the sustainable management of water resources.

2.2 Climatic and non-climatic drivers

2.2.1 Climatic drivers

Climate change and uncertainties have become additional concerns which are likely to exacerbate the differences in plans, strategies, programmes and actions between upstream and downstream countries. Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity (IPCC, 2007).

The IPCC (2007) reported that precipitation, temperature, and evaporation are the most prevailing climatic drivers for water availability. Temperatures are anticipated to rise during all seasons of the year, although with different increments, while precipitation may increase in one season and decrease in another. In a related context, Christensen et al. (2007) and Sillmann and Roeckner (2008) pointed out that extreme precipitation is projected to increase significantly, particularly in regions that are relatively wet in the present-day climate condition, whereas dry spells are foreseen to rise especially in regions characterized by a dry climate condition. The World Bank (2009) indicated that by the end of the 21st century, a global warming between 1.1°C and 6.4°C is likely to occur, depending on the emission path. There is much disagreement and uncertainty, however, concerning the magnitude and rate of future global warming.

It was also reported that by the mid-21st century, high altitudes and some wet tropical areas are expected to witness an increase in runoff between +10% and +40%, while some dry regions at mid-latitudes and in the dry tropics are anticipated to experience a decrease between –10% and –30% (IPCC, 2007; Sillmann &

Roeckner, 2008). Kusangaya et al. (2013) have pointed out that runoffs for some rivers in southern Africa such as the Zambezi, Pungwe and Okavango are projected to decrease by –20%, –75% and –20%, respectively, by 2050. In a related context, the World Bank (2009) has reported that for the MENA region, the anticipated decline in rainfall and runoff falls between –10 % and –25% and between –10 % and –40%, respectively and the foreseen increase in evaporation lies between +5 % and +20%.

The United Nations Development Programme in Iraq (UNDP-Iraq, 2011) stated that Iraq and Iran, among other countries in the Middle East (ME), have experienced series of acute droughts since 1999. This can be imputed to the impact of climate change (downward trend of precipitation, and rising tendencies in temperature and potential evapotranspiration rates), which still needs to be verified for the entire basin.

The FAO (2011) has reported that both rainfall and temperatures are predicted to become more variable, with a consequent higher incidence of droughts and floods, sometimes in the same place. However, the UNECE (2011a) has reported that, although there is still a lot of uncertainty about the impacts of climate change in many regions and basins, the weather will be more extreme, with more frequent and more intense droughts and floods. Runoff patterns are harder to anticipate as they are governed by land use as well as uncertain changes in rainfall amounts and patterns. According to the World Bank (World Bank, 2009, 2014a), the climate change will affect agriculture through higher temperatures and more variable rainfall, with substantial reductions in precipitation likely in the mid-latitudes where agriculture is already precarious and often dependent on irrigation.

Water resource availability will be altered by changed rainfall patterns and increased rates of evaporation.

The FAO and the National Drought Mitigation Centre (NDMC) of the University of Nebraska-Lincoln, Nebraska, USA (FAO-NDMC, 2008) provided some information (Table 2-1) for Western Asia (between 12^{o}N and 42^{o}N, and between 27^{o}E and 63^{o}E) for the likely increase in temperature and decrease in precipitation between 2010 and 2099 for two climate change scenarios (A1F1 and B1).

Table 2-1: Projected increase in temperature and decrease in precipitation between 2010 and 2099 for two climate change scenarios (A1F1 and B1) (FAO-NDMC, 2008).

	2010-2039			
Season	Temperature ^{o}C		Precipitation %	
	A1F1	B1	A1F1	B1
DJF	+1.26	+1.06	−3	−4
MAM	+1.29	+1.24	−2	−8
	2040-2069			
DJF	+3.10	+2.00	−3	−5
MAM	+3.20	+2.20	−8	−9
	2070-2099			
DJF	+5.10	+2.80	−11	−4
MAM	+5.60	+3.00	−25	−11
D: December, J: January, F: February, M: March, A: April, and M: May				

Several studies have assessed the climate change impact on surface water hydrology (Fowler, Kilsby, & Stunell, 2007; Ardoin-Bardin et al., 2009), reservoir management (Minville et al., 2009), and recharge to groundwater aquifers (Scibeck & Allen 2006; Jyrkama & Sykes, 2007; Holman, Tascone, & Hess, 2009).

Groundwater aquifers are not only subjected to the natural recharge variability but further influenced by groundwater extraction for irrigation and human and livestock demands. Two main opposing effects of irrigation on aquifer dynamic systems were identified: depletion in the contribution of groundwater in primarily groundwater-fed irrigation areas, and the increase of groundwater in areas dominated by return flows from irrigation fed by surface water. In irrigated areas, both climate change and groundwater abstraction have to be integrated in order to properly study the evolution of groundwater resources.

2.2.2 Non-climatic drivers

Many non-climatic drivers such as land-cover modifications, population growth, industrial development and demographic change affect freshwater resources at the global scale (IPCC, 2007; World Bank, 2009). Water resources, both in quantity and quality, are influenced by anthropogenic pressures such as impoundment of reservoirs and water hydraulic diversion to supply irrigation projects, and domestic and industrial consumers. The USAID (2012) has highlighted the major challenges to climate change adaptation. These challenges include but not limited to data and information gaps, inadequate coverage of hydro-meteorological stations, lack of coordination across agencies, limited capacity to develop and implement adaptation plans, limited understanding of adaptation concepts by policy makers, lack of public awareness and weak engagement of civil society, inefficient irrigation practices, financial constraints and lack of clear and consistent policies and regulations.

A close examination of literature (Kundzewicz et al., 2007; Arnell & Charlton, 2009; Hall et al., 2012; Antwi-Agyei, Dougill, & Lindsay 2013) shows that there are four main barriers and limits that may impede the process of adaptation to climate change.

These barriers are: physical (i.e. deteriorated infrastructure), economic (i.e. lack of financial resources), socio-political and capacity of water management institutions (i.e. lack of coordination, lack of active programmes and insufficient knowledge).

Man-made disturbances twinned with prolonged drought episodes have noticeably intensified water management challenges (International Union for Conservation of Nature [IUCN], 2000; Rosenberg et al., 2000; Montenegro & Ragab, 2012; Al-Faraj & Scholz, 2014a,b).

The literature materials provide examples on efforts that have been conducted to analyse hydrologic alterations and characterize the impact of river regulation on flow paradigms (Olden & Poff, 2003; Shiau & Wu, 2004a; Monk et al., 2007; Gao et al., 2009; Zolezzi et al., 2009).

The growth of collective influence has explicitly elevated the level of concern and sounded the alarm about the potential hydro-environment adverse consequences on water availability in the downstream states. The World Bank (2009) reported that the future is expected to encounter more discord and higher conflict among riparian countries, sectors, communities, and individuals over water.

Increasing development and abstraction of transboundary waters at small to large scale could interact with climate variability to exacerbate existing latent tensions between riparian countries. Miller and Yates (2006) have underlined that it is important to understand how environmental change may disturb water resources which riparian countries depend on and compete over. Despite the continuing efforts to reach agreements on shared water apportionment, the current predominant tendency is that the upstream countries seek continuously to unilaterally and excessively exploit the transboundary waters on their territories.

2.2.3 Uncertainties associated with climate change

Despite the noticeable development in Global Climate Models (GCMs) that project the potential future climate changes according to various scenarios, there are uncertainties associated with the outcomes of these models (IPCC, 2007, 2013, 2014). The IPCC (2013) reported that the GCMs depict the climate using a three-dimensional grid over the globe, typically having a horizontal resolution of between 250 and 600 km, 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans. The GCMs operate at quite coarse resolution relative to the scale of exposure units in most impact assessments, which make them inappropriate for spatial assessments at basin, national or sub-national levels. However, there are still areas for further improvement related to (1) scale and spatial representation (125 to 400 km grid cells at present); (2) land-surface atmosphere interactions and their representations; (3) the trends and behaviour of aerosols in the atmosphere (FAO, 2011).

Climate variability is likely to increase, though it is harder to predict by how much and over what time period (FAO, 2011). The uncertainty is not limited to the findings, but it extends to the reliability of the historical data, magnitude of the impact and how well the decision and action will handle and soften the adverse impact. Hall et al. (2012) have pointed out that uncertainty has always been a decision-making challenge in water resources management. The future discloses a spectrum of major stressors that would result from climate change, population growth, demographic change, land use and socio-economic drivers.

Adaptation to climate change is increasingly featuring in the water companies' investment plans. Set out principles for how water resources management planning can be put on a more rational risk-based footing and sketch out a potential implementation. Moreover, Hall et al. (2012) have highlighted that there are many uncertainty factors besides climate change that will also affect the supply–demand balance over future decades. These could include changes to the way of controlling the present-day water withdrawal arrangements to protect the environment, population growth and water consumption practices, and changes in watershed hydrology as a result of landscape modification.

2.2.4 Climate storylines and scenarios

The IPCC Special Report on Emissions Scenarios (SRES) adopts four narrative "storylines" or "scenario families" labelled, A1, A2, B1, and B2. These storylines describe how the world populations, economies and political structures — forces driving greenhouse gases (GHGs) and aerosol emissions — may evolve during the 21st century. The 'A' scenarios focus on economic growth, the 'B' scenarios on environmental protection, the '1' scenarios assume more globalization and the '2' scenarios assume more regionalization (Houghton et al., 2001; IPCC 2001, 2007, 2013, 2014).

2.3 Synthetic scenarios of climate change

Synthetic scenarios, sometimes referred to as arbitrary scenarios, are based on incremental changes in climatic elements (mean air temperature and/or precipitation amount) by an arbitrary amount, for example, temperature changes of +2ºC and +4ºC can be combined with precipitation changes of 10% or 20% or no change in precipitation to create a synthetic scenario (IPCC, 2007). These incremental changes are usually combined with a baseline daily climate database to yield an altered 30-year record of daily climate. Synthetic scenarios usually assume a uniform annual change in temperature and other variables over a study area.

Synthetic climatic scenarios are easy to create and the results can be quickly obtained. They provide information on a range of possible changes. The relative sensitivity of the object of study to the changes in climate can be quickly explored. The disadvantages are that they seldom represent a realistic set of changes that are physically plausible, particularly if uniform changes are applied over a very large area or if assumed changes in variables are not physically consistent with each other (Cics.uvic.ca, 2000).

Frederick (1997) has summarized the results (Table 2-2) of some simulation studies carried out using synthetic scenarios. The studies covered five semi-arid river basins to examine the result of temperature and precipitation changes on the mean annual runoff. Two incremental changes in temperature were considered as (T+2°C) and (T+4°C), whereas three scenarios in precipitation change were taken into account as −10%, no change and +10%.

Table 2-2: Impacts of climatic change on mean annual runoff in five semi-arid river basins (Frederick, 1997).

Change in precipitation (%)	River	Temperature change: Tmean+2°C	Temperature change: Tmean+4°C
		Change in mean annual runoff	
−10%	Sacramento river	−18%	−21%
	Inflow to lake Powell	−24%	−32%
	White river	−13%	−17%
	East river	−19%	−25%
	Animas river	−17%	N/A
0%	Sacramento river	−3%	−7%
	Inflow to lake Powell	−12%	−21%
	White river	−4%	−8%
	East river	−9%	−16%
	Animas river	−7%	−14%
+10%	Sacramento river	+12%	+7%
	Inflow to lake Powell	+1%	−10%
	White river	+7%	+1%
	East river	+1%	−3%
	Animas river	+3%	−5%

In the case of no change in precipitation, estimated mean annual runoff declines by −3% to −12% with a 2ºC increase in temperature; with a 4ºC increase, runoff drops by −7% to −21% simply. This can be attributed to a rise in evapotranspiration. A 10% rise in precipitation does not fully substitute the adverse impacts on runoff attributable to a 4ºC increase in temperature in three of the five rivers for which this climate scenario was studied. Likewise, an increase in precipitation of +10% and +2ºC in temperature shows an increase of +1% in runoff in two rivers and +3% in one of the examined rivers, whereas the White and Sacramento rivers show a higher response of +7% and +12% respectively. With a decline in precipitation of −10% and a warming by +2ºC and +4ºC, the decline in runoff falls between −13% and −32%.

2.4 Adaptation to climate change in water sector

Since the beginning of the 21st century, climate-change related problems and adaptation have received growing attention and interest at national and international levels by climate change and adaptation communities. Examples of recent research work are documented in (Hiscock, Rivett, & Davison, 2002; Ragab & Prudhomme, 2002; Conway, 2005; Kundzewicz et al., 2007; Kistin & Ashton, 2008; Arnell & Charlton, 2009; Goulden et al., 2009; Timmerman & Bernardini, 2009; Tompkins et al., 2009; UNECE, 2009; Keskinen et al., 2010; Timmerman et al., 2011; United States Agency of International Development [USAID], 2012; Hall et al., 2012).

Literature materials (Kundzewicz et al., 2007; Arnell & Charlton, 2009; Hall et al., 2012; Antwi-Agyei, Dougill, & Lindsay 2013) show that the adaptation options were mainly categorized into four groups: (1) supply-side (2) demand-side (3) trade-offs among sectors and (4) flood protection. With respect to developing adaptation strategies at transboundary development scales, the IPCC (2001) reported that the current knowledge of adaptation and adaptive capacity to climate change is insufficient, and there are serious limitations in existing evaluations of adaptation measures. Goulden et al. (2009) have pointed out that few studies address adaptation to climate change in transboundary river basins. The UNECE (2010) has indicated that in most cases, adaptation strategies are developed without taking transboundary aspects into account.

Mosera and Ekstromc (2010) have defined three main phases of the adaptation process. Each of these process phases includes a series of stages (for a total of nine stages).

These phases are: (a) understanding; (b) planning; and (c) managing. Understanding consists of the stages of (1) problem detection resulting in an initial shaping of the problem; (2) data gathering and use of information to properly understand the examined problem; and (3) re-definition of the problem, that may need further examination. Planning encompasses (1) development of adaptation options; (2) assessment of potential options; and (3) selection of appropriate option(s). Finally, the management phase comprises (1) implementation of the selected option(s); (2) observing the environment and the results of the realized option(s); and (3) findings assessment. Figure 2-6 illustrates the adaptation phases and the associated sub-processes (Mosera & Ekstromc, 2010).

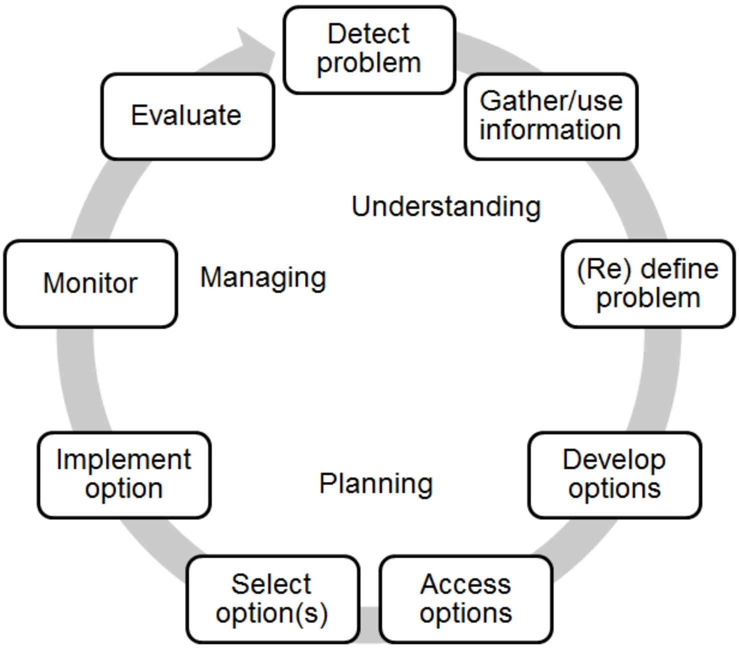

Figure 2-6: Phases and sub-processes throughout the adaptation process (*After* Mosera & Ekstromc, 2010).

The UNECE (2009, 2010, 2011a) and FAO (2012a) highlighted the need to develop adaptation strategies to cope with the range and depth of anticipated climate change impacts. Mitigating or adaptive actions by an individual state to address potential climate change impacts in a shared river basin are unlikely to achieve the objective (Swain, 2011).

Despite the essential endeavours and investments in adaptation options research work, no functional on-ground adaptation actions have been accomplished (Wise et al., 2014). There is a need to focus on enabling decision makers to make the difficult and urgent choices between a range of alternative policy and management options in interconnected social and natural systems. The climate adaptation is not separable from the cultural, political, economic, environmental and development contexts.

The Gross Domestic Product (GDP) can be taken as an indication of national economic resources available for adaptation and the Human Development Index (HDI) as an indication of socio-economic vulnerability to climate change impacts. The HDI is expressed as a value between 0 and 1. The closer to 1 the score is the higher the level of human development. The UNDP (2014) has reported that Iraq's 2013 HDI was 0.642, which is in the medium human development category, positioning the country at 130 out of 187 countries. Iran's HDI was 0.742, which is in the high human development category, ranking the state at 76. In the same context, the Legatum Institute in the UK has proposed a Legatum prosperity index that ranks countries according to their performance across eight equally-weighted sub-indices such as economy, education, health and safety and security (Legatum Institute, 2014). Iraq and Iran rank globally in 2014 at 128th and 107th respectively, out of 142 states.

2.5 Hydrologic anomaly

The growing water demand for irrigation and public water supply have highlighted the need for broader and deeper understanding of the impacts of anthropogenic pressures and water abstraction on riverine systems, especially in shared river basins. The hydrologic regime of a river is defined by several descriptors such as magnitude, timing, frequency, duration and rates of change of runoff (Poff et al., 1997).

The critical challenge in sustainable management of water resources of a transboundary river among riparian states is the determination of the degree to which the natural flow regime has been altered. Water management activities are often undertaken to meet multi-user water demands and to minimize risks of extreme events with inadequate consideration of maintaining healthy river ecosystems. Documenting the degree to which streamflow has been modified by cumulative effects of increasing water withdrawals is critical for integrated water resources management.

Concerning many rivers, runoff is greatly impacted by human activities such as reservoir inaugurations, large-scale irrigation schemes, water supply for municipal and industrial uses, and fish farms. Anthropogenic perturbations in the upstream riparian country produce a flow regime in the downstream state that differs considerably from that of the unimpaired condition. Petts (1980) has stated that for thousands of years humans have managed riverine systems to provide a secure supply of water for consumption.

Although human-related alteration of hydrologic regimes is subject to landscape modifications, channelization of streams and groundwater abstraction

(Vorosmarty & Sahagian, 2000), inauguration of reservoirs usually causes the greatest shift in flow regime attributed to anthropogenic forces (Magilligan et al., 2003). Damming entire rivers can be a great challenge (Poff et al., 2007).

Literature shows that considerable research work has been carried out on impacts of human intervention on natural flow regimes, maintaining a healthy river ecosystem and assessing hydrologic alterations (Richter et al., 1996; Richter et al., 1997; Poff et al., 1997; Richter & Richter, 2000; Maingi & Marsh, 2002; Kiesling, 2003; Olden & Poff, 2003; Choi, Yoon, & Woo, 2005; Gao et al., 2009).

Recent studies have assessed modifications of riverine systems. Most studies are relevant to large river systems and various forms of associated river regulations. Several assessment methods have been developed such as the Range of Variability Approach (RVA) (Richter et al., 1996), the Suen and Eheart method (Suen & Eheart, 2006), the Histogram Matching Approach (HMA) (Shiau & Wu, 2008) and the Frequency Based Approach (FBA) (Principato & Viggiani, 2012).

The literature reveals that limited research work has been performed on hydrologic alterations regarding transboundary river watersheds. Some of the work focused on man-made alterations (Kummu & Sarkkula, 2008; Wilk et al., 2010; Lauri et al., 2012), while others were concerned with the cumulative impact of human-induced alteration and climate change (Mango et al., 2011; Kuenzer et al., 2013). However, anthropogenic river regulation, hydropower development, reservoir operation and land use changes were among other components assessed with respect to artificial alteration. Moreover, the impact of drought and water management on various hydrological systems has been highlighted by Lorenzo-Lacruza et al. (2010).

The Indicators of Hydrologic Alteration (IHA) model of the Nature Conservancy developed by Richter et al. (1996) has been extensively adopted in evaluating the hydrologic alteration attributable to human disturbances. The method compares the hydrology of a reference 'unaltered' regime to an 'altered' paradigm. This model consists of 33 hydrologic measures that are ecologically meaningful and sufficiently sensitive to capture anthropogenic changes to riverine systems. These indices are grouped into five major categories: (i) magnitude, (ii) magnitude and duration of annual extreme conditions, (iii) timing of annual extreme conditions, (iv) frequency and duration of high and low pulses, and (v) rate and frequency of changes in conditions (Richter et al., 1996; Richter et al., 1997; Richter & Richter, 2000; Shiau & Wu, 2004a,b; Gao et al., 2009). Olden and Poff (2003) have stated that the wide application of hydrologic indices for describing various aspects of flow conditions has resulted also in their increased utility in river systems research.

The RVA method uses IHA outputs and compares the frequency of occurrence for the same parameters. This method allows users to determine how often a specific parameter in the 'post-regulation' condition falls within the same statistical quartile as the 'predevelopment' data. Both the RVA and IHA methods can be modelled using the IHA Software (Richter et al., 1996).

With a large number of competing hydrologic indices, two main drawbacks can be recognized: (1) considerable computational effort, and (2) redundancy of variables. It follows that researchers are now challenged with the task of developing a small set of metrics for assessing generic hydrologic alterations while representing major facets of the hydrologic anomalies in natural flow regimes. Sahin and Hall

(1996) have pointed out that despite the progress made in identifying the likely implications of various landscape modifications and river damming, there is still considerable need to either improve the existing tools or develop new ones to support water resources planners and managers in dealing with specific impacts of land use modifications and river regulations in shared watersheds.

2.6 Flow hydrograph separation techniques

Hydrograph separation techniques generally divide the total runoff hydrograph into a quick component and a delayed component (World Meteorological Organization [WMO], 2009a). The delayed flow component is commonly referred to as the baseflow (Q_b) that originates from groundwater storage. Baseflow is an important component of a streamflow hydrograph, which comes from groundwater and shallow subsurface storages. Welderufael and Woyessa (2010) and Brodie and Hostetler (2005) have underlined the importance of baseflow isolation and interpretation of its magnitude for the development of water management strategies. Smakhtin (2001a,b) has stated that the baseflow forms the entire runoff during dry periods.

The non-dimensional ratio between the flow volume under the isolated hydrograph and the flow volume under the total runoff hydrograph is referred to as the baseflow index (BFI). Smakhtin (2001b) reported that the BFI was further developed by the Institute of Hydrology in a low-flow regime study for the United Kingdom, characterizing the hydrological response of soils and geology of the watershed.

The BFI has been used not only in the United Kingdom, but also in low-flow studies in mainland Europe, New Zealand, East Africa (Abebel & Foerch, 2006), South Africa and the Himalayas (WMO, 2009a), Palestine (Shadeed, Shaheen, & Jayyousi, 2007), Slovakia (Brušková, 2008) and the USA (Ahiablame et al., 2013; Zhang et al., 2013). The BFI values can vary between 0.15 and 0.20 for an impermeable catchment and to more than 0.95 for a flashy flow regime such as basins with high storage capacity and a stable flow regime. The BFI is related to climate, topography, vegetation, soil type and geology within a watershed, and is seen as the most dominant low-flow indicator (Haberlandt et al., 2001; Longobardi & Villani, 2008).

Numerous techniques have been developed for hydrograph analysis to separate the baseflow from measured runoff hydrographs (Lim et al., 2010).

Graphical separation methods are used to plot the baseflow component of a flood hydrograph event, including the point where the baseflow intersects the falling limb. These methods are constant discharge, constant slope, the concave method and the master depletion curve method (Brodie & Hostetler, 2005). However, these are subjective techniques, which do not provide consistent results, even with the same flow data (Lim et al., 2005).

The baseflow is an index of the watershed's ability to release water from groundwater storage during a dry period (Gregor, 2010). Likewise, a high BFI would imply that a river basin has a more stable flow condition, and is able to maintain runoff during a lengthy dry period. Tallaksen and Lanen (2004) stated that information on hydrogeological properties and geology supports the derivation of a storage index. The determination of the baseflow component of stream flow is necessary to understand the hydrologic budgets of surface and ground water resources. Price (2011) stated that the baseflow is generally influenced by basin characteristics such as physiographic features, aquifer characteristics, evapotranspiration, geomorphology, landscape modifications and soil types.

Digital filtering algorithms have become most frequently used in hydrograph analysis (Eckhardt, 2005; Lim et al., 2005; Lim et al., 2010). The most widely used one-parameter digital filtering algorithms are expressed in Equations 2.1 and 2.2 developed by Lyne and Hollick (1979, cited in Welderufael & Woyessa, 2010) and Chapman (1991, cited in Welderufael & Woyessa, 2010).

$$q_t = \alpha q_{t-1} + 0.5(1+\alpha)(Q_t - Q_{t-1}) \qquad \text{Equation 2.1}$$

$$q_t = \frac{(3\propto -1)}{(3-\propto)} q_{t-1} + \frac{2}{(3-\propto)}(Q_t - \propto Q_{t-1}) \qquad \text{Equation 2.2}$$

where q_t is the filtered direct runoff at a time step t (m^3/s); q_{t-1} is the filtered direct runoff at a time step t–1 (m^3/s); α is the filter parameter (-); Q_t is the total runoff at time step t (m^3/s); and Q_{t-1} is the total runoff at time step t–1 (m^3/s). As far as the first two equations are concerned, the baseflow is $q_b = Q_t - q_t$.

Eckhardt (2005) has pointed out the similarity between filtering direct runoff from a baseflow, and signal analysis and processing. The latter technique has been applied in isolating baseflow from total runoff, because high and low frequency waves can be associated with the direct runoff and the baseflow, respectively. Eckhardt (2005) introduced a two-parameter digital filtering algorithm featuring the filter parameter (α) and the maximum value of the BFI, BFI_{max} (Equation 2.3; known as Eckhardt's formula).

$$q_b = \frac{(1-BFI_{max})\propto q_{b-1} + (1-\propto)BFI_{max}Q_t}{1-\propto BFI_{max}} \qquad \text{Equation 2.3}$$

where q_b is the filtered baseflow at the time step t; q_{b-1} is the filtered baseflow at the time step t–1; $BFI_{\max}$ is the maximum value of the long-term ratio of baseflow to total stream flow; α is the filter parameter; and Q_t is the total stream flow at the time step t.

Smakhtin (2001b) has pointed out that as a general rule, the filter parameter value of 0.925 is perceived to be a good starting point for most of the monthly baseflow isolations. It is likely to be applicable for monthly baseflow separations in regions where average annual precipitations are in the range of approximately 600 mm to 1100 mm. In semi-arid and arid climate regions with mean annual precipitations of less than an arbitrary threshold of 600 mm, the filter value may be increased by about 2%. The filter may be lowered similarly for regions where average yearly precipitation is over 1100 mm. Stewart, Cimino and Ross (2007) have reported that the filter parameter does not depend on physical processes in runoff watersheds, which makes it difficult to objectively asses its accuracy. However, the filter parameter affects the degree of attenuation.

Eckhardt (2005) found that the filter parameter (α) is not very sensitive to the filtered results (Equation 2.3), while the $BFI_{\max}$ value greatly impacts the results. Three representative $BFI_{\max}$ values for different hydrological and hydrogeological conditions were introduced; 0.80 for perennial streams with porous aquifers, 0.50 for ephemeral streams with permeable aquifers, and 0.25 for perennial streams with hard rock aquifers. The disadvantage of this approach is the need for isolated storm hydrographs, which are often either hard to find or not available.

Lim et al. (2010) have developed a genetic algorithm (GA) analyser to compute the optimum $BFI_{\max}$ and filter parameter values to be used in the Eckhardt digital filtering method. The computation process is to compare the filtered baseflow with the baseflow from recession curve analysis until the maximum Nash-Sutcliffe coefficient value is obtained.

In recession analysis methods, recession curves are the parts of the hydrograph that are characterized by the release of water from natural storage sources, typically assumed to be groundwater discharge. Recession segments are selected from the hydrograph and can be individually or collectively analysed to gain an understanding of the discharge processes that make up the baseflow (Brodie & Hostetler, 2005). Smakhtin (2001a,b) and Brodie and Hostetler (2005) have pointed out that one of the most well-known techniques is the UK smoothed minima method, which uses the minima of five-day non-overlapping time intervals to isolate the baseflow.

Frequency-duration analysis, which is also known as Flow Duration Curve (FDC) analysis, is another widely used technique to analyse the characteristics of a stream flow (Welderufael & Woyessa, 2010). Moreover, this analysis technique is the most informative means of showing the full range of stream flows; from low flows to flood events (Smakhtin, 2001a). The ratio of Q90 (i.e. the flow observed ≥90% of the time) to Q50 (i.e. the flow recorded ≥50% (median) of the time), which is obtained from the flow duration curve analysis, is the commonly used index to identify the ground water storage contribution to the total runoff or the percentage of the baseflow component.

Smakhtin (2001a) has indicated the use of three indices extracted from the flow duration curve to (1) reflect streamflow variability, (2) represent low-flow discharges variability and (3) interpret the groundwater contribution to total runoff.

These indices are: Q20/Q90, Q50/Q90 and Q90/Q50, respectively. Pyrce (2004) has used some common percentiles: Q70, Q90 and Q95 as low flow indices.

The United Nations Environment Programme Agency (UNEPA, 2011) has grouped the FDC intervals into five zones to provide additional insight on conditions and changes associated with the impairment. These zones are high flow (0-10% of time), moist condition (10-40% of time), mid-range flows (40-60% of time), dry condition (60-90% of time), and the low flows (90-100% of time). This categorization places the midpoints of the moist, mid-range, and dry zones at the 25th, 50th, and 75th percentiles, respectively. The high zone is centred at the 5th percentile, while the low zone is centred at the 95th percentile. Although five zones are commonly used to derive additional information from the FDC, the number of zones and range of frequency values can be adjusted based on local hydrologic conditions.

2.7 Water abstraction for irrigation and efficiency of irrigation system

Agriculture is the largest water consumer of freshwater worldwide, with irrigation abstractions accounting for approximately 71% of the total annual water withdrawal (Fischer et al., 2007; 2030WRG, 2012). Of this, about 50% is estimated to be consumed by the crop – the remainder is lost during storage, conveyance and sub-surface drainage after application (Jury & Vaux, 2007). In many developing countries, a higher proportion of approximately 80% of annual water withdrawal is used in agriculture (Turral, Svendsen, & Faures, 2010), indicating the dependence on water for food crop production for rural communities (Knox, Kay, &

Weatherhead, 2012). Zubari (2002) has pointed out that water losses accounts for at least 45% of water used in irrigated agriculture in most of the West Asia countries, which arises from inefficient irrigation systems. He also highlighted the importance of improving efficiency to minimize the water losses.

The FAO (2011) reported that the likely increased rate of evaporation and changed rainfall patterns in the mid-latitudes — the areas where agriculture is already precarious and often dependent on irrigation — due to climate change will possibly suffer from increased water requirements. The FAO (2014) indicated that the agriculture sector is the predominant user of the available freshwater resource in Iraq and Iran compared with non-agriculture sectors such as municipal and industrial.

The volume of water abstracted for irrigated agriculture falls in the range of 80% to 94% of the total annual water withdrawal. With respect to the total annual abstracted water, Iraq witnessed a drop of about 19% in the water withdrawal for irrigation over the period 1987-2000. The proportions were 97.5%, 92.0% and 84.0% for the years 1987, 1992 and 1997. Between 2000 and 2009, the proportion remained steady at approximately 79% (Word Bank, 2014b; Panahi et al., 2009). In Iran, the percentage hovered around 93% between 1995 and 2009. The proportions were 91.6%, 93.4%, 92.2% and between 92% and 94% for the years 1995, 2001, 2004 and 2009, respectively (Word Bank, 2014b; Panahi et al., 2009).

In the same context, the World Bank (2014b) reported that the percentages of water withdrawal for agriculture with respect to the total annual water withdrawal between 2008 and 2012 were 92% and 79% for Iran and Iraq, respectively.

However, the FAO (2011) has reported that the agriculture sector in Iraq uses about 85% of the total abstracted water.

Literature showed that, world-wide, irrigated agriculture is the main water use sector, particularly in South Asia, the MENA region, Sub-Saharan Africa, and East Asia and Pacific (Pereira, 2004). The proportions ranged from 86% to 94%. On a global scale, irrigated agriculture uses between 70% and 80% of all water withdrawals (Peter, 2004; UN-WWDR, 2014). Pereira (2004) and the UN-WWDR (2014) pointed out the importance of increasing the ISP_{Eff} and reducing the water losses through improving the knowledge-based irrigation demand management, which provides reliable and flexible water application.

In countries where irrigated agriculture occupies the first rank in water withdrawals such as Iraq, Iran, Turkey, Syria, Kenya, Pakistan and Afghanistan (FAO, 2012b), the efficiency of the irrigation system plays a crucial driver in water saving and the wise use of water resources. Recent frequent drought spells and climate change risks have added additional pressures on water managers to sustainably manage the available water resources and minimize wastage in water use. Keshavarz, Heydari, and Ashrafi (2003) suggested that the efficiency of the irrigation systems in Iran ranges between 33% and 37%, lower than the average for both developing countries (45%) and developed countries (60%).

Some other references (Nikkami, 2009; Panahi et al., 2009) showed that the current efficiency of irrigation systems in Iran is between 23% and 50%. Moreover, Rasouliazar (2011) has indicated that the irrigation efficiencies of the traditional irrigation methods (i.e. surface, basin and border) in Iran range between 23% and 32%. Nikkami (2009) pointed out that on average, the ISP_{Eff} of the basin's portion which spans Iran is estimated at about 40%. The present ISP_{Eff} in the Diyala basin in Iraq can be estimated at about 40% (Ministry of Water Resources [MoWR], 2011, unpublished data). Radmanesh (2002, cited in Rasouliazar, 2011) argued that with a 5% increase in irrigation efficiency, the annual volume of water that would be saved accounts for 4 billion m^3.

The USAID (2004) and the World Bank-FAO (2011) reported that improving on-farm irrigation efficiency in Iraq from the low current levels, anticipated to be 30% to 40% but likely about 20% or less, to a much higher level would considerably reduce the amount of water allocated for irrigation. At any rate, despite some discrepancies observed in some of the figures concerning irrigation efficiencies, the consensus is that the water withdrawal for agriculture largely exceeds that for any other sector in many countries, yet the agriculture sector is the least efficient one. This confirms the paramount importance of improving the efficiency of irrigation water-related systems such as water delivery and distribution systems, and minimizing the losses.

2.8 Drought categories and indices

2.8.1 Drought categorization

Drought is a worldwide concern. It occurs over most parts of the world, in both dry and humid areas (WMO, 2006). Wilhite and Glantz (1985) completed a thorough review of dozens of drought definitions and identified four categories: meteorological, agricultural, hydrological and socio-economic.

Meteorological drought: Refers to a considerable negative departure of precipitation from the normal condition, over an extended period of time. The historical normal (average) is often based on 30-year period of records (FAO, 2008).

Agricultural drought: Defined by a drop in soil moisture availability below the optimal level required by a crop during each different growth stage, resulting in impaired growth and reduced yields. The soil moisture deficit in the root zone during various stages of the crop growth cycle has a profound impact on the crop yield. Agriculture is usually the first economic sector to be affected by drought (University of Florida, 1998; Sivakumar et al., 2011). The agricultural sector would be a primary beneficiary of improved drought monitoring, early warning, and decision support tools that would reduce the impacts of drought on the society, the economy and the environment (Wilhite, 2010).

Hydrological drought: Results when precipitation deficiencies begin to reduce the availability of natural and artificial surface and subsurface water resources. It occurs when there is a substantial deficit in surface runoff below normal conditions or when there is a depletion of ground water recharge. There is a time lag between lack of rain and less water in streams, rivers, lakes and reservoirs, so hydrological measurements are not the earliest indicators of drought (University of Florida, 1998). Duration and water shortage volume are the most important factors for the estimation of the level of hydrological drought severity (Tomaszewski, 2011).

Socio-economic drought: Occurs when the health, well-being, quality of life and human activities are affected by imbalance between water availability and demand. The progression of drought and the relationship between meteorological, agricultural, and hydrological drought is shown in Figure 2-7 (National Oceanic and Atmospheric Administration [NOAA], 2006). Understanding the historical frequency, duration and spatial extent of drought episodes and identification of the most vulnerable water-using sectors assists researchers, decision-makers and drought planners in minimizing the implications of the use of crisis-based management strategies (Quiroga et al., 2011; Wilhite, 2011; Estrela & Vargas, 2012). Moreover, it eases the gradual transition to risk planning at the transboundary scale, where there is an increased need for the riparian states to communicate, coordinate and cooperate (Milman et al., 2013).

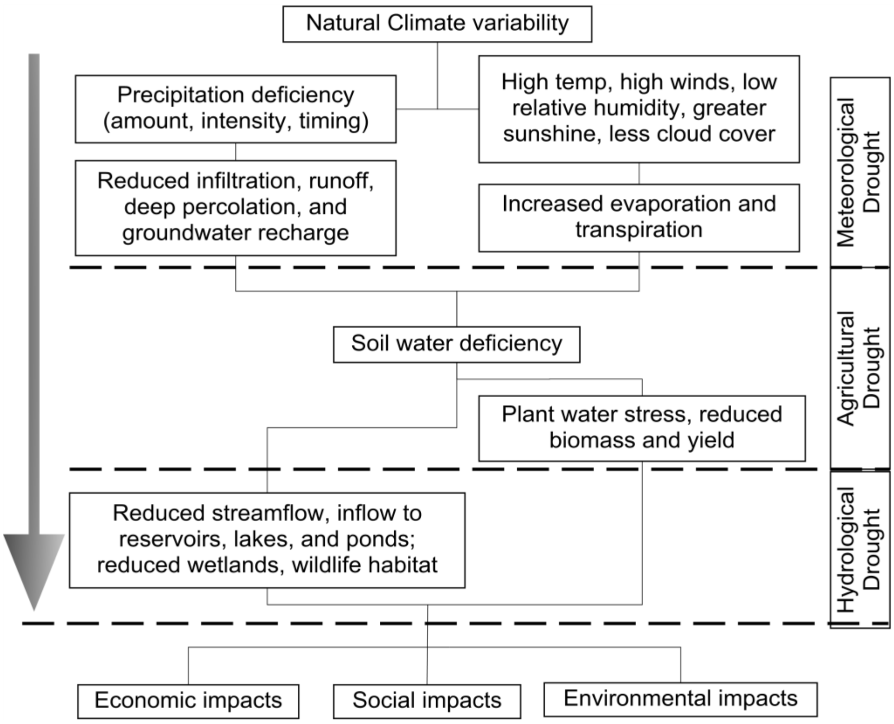

Figure 2-7: Progression of drought and the relationship between meteorological, agricultural, and hydrological drought (*After* NOAA, 2006).

2.8.2 Challenges and constraints for drought mitigation in Iraq

Since 2010, concern has grown in Iraq about the fragility of handling the recent droughts and the inadequacy of current drought management practices.

Droughts have singular features (e.g., unpredictability, slow and progressive onset, wide and blurred distribution both in time and space, non-structural and diffuse impacts), which have favoured a reactive post-disaster crisis response (Do Ó, 2012).

The current water policy is largely confined to treat the symptoms of droughts rather than taking proactive measures to decrease the vulnerability of the water systems. The key factors contributing to the increased system vulnerability include the (a) possible impact of climate change, (b) deficiency of appropriate and timely needed precipitation, (c) growing water demand at national level, (d) significant reduction in annual flow volume entering Iraq from upstream riparian states, (e) deterioration of water quality due to both discharges of untreated hazardous industrial wastes and return flows from irrigation projects into rivers, (f) lack of efficient water use and management and (g) weakness in qualified human-resources and institutional capacities.

Recognizing the urgent need to comprehensively tackle the situation, the Government of Iraq has thus called on the United Nations to provide support in formulating a national framework for integrated drought risk management (UNDP, 2013a,b). The objectives are to support Iraq to implement a series of technical assessments of present drought risk management measurements and weaknesses, and perform a series of consultations and consensus-building activities to shape a nation-wide strategy for mitigating drought impacts and risk management processes.

The current drought management policy in Iraq seems flawed in terms of the time frame for action to take place and the range of spatial coverage. Effective management actions often follow drought periods. Relief measures are commonly delayed well beyond the time span when the assistance would have been most needed in addressing the symptoms of drought. The obstacles concerning the establishment of short- to long-term risk drought management strategies in Iraq are plentiful and diverse (Al-Faraj et al., 2014e). These obstacles are:

a) There is a lack of knowledge and common understanding of pre-emptive drought short- to long-term planning and management associated with multiple scenarios.
b) Deficiencies exist in institutional and technical capacities at the operational and strategic levels to respond to drought. Moreover, there is an absence of consensus among governmental institutions on issues related to drought management.
c) There is a deficit in reliable data on historical drought consequences in various sectors. Furthermore, there is also little transparency in exchange of the data, which are disseminated by institutional stakeholders such as the Ministry of Water Resources, Ministry of Agriculture, Ministry of Environment, Ministry of Planning, Ministry of Municipalities and Public Works, and Ministry of Agriculture and Water Resources in the Kurdistan region of Iraq. Large differences in the capacity and willingness of various groups to provide or to handle information exist. Data, if available, are in different formats, often incomplete and not regularly updated.
d) Responsibilities, coordination and actions regarding Drought Risk Management (DRM) are fragmented, and commonly inconsistently administered among governmental bodies and their local departments.

e) Drought remedies are biased towards relief measures in the form of reactive assistance programmes in an attempt to accelerate the pace of the recovery process through provision of money or other specific types of support (e.g., livestock feed, distribution of water via water tanks, food provision and rapid deep well extraction licence approvals) to those experiencing the most severe impacts of the drought (FAO, 2008). The government often acts after the onset of symptoms of drought and their activity usually wanes when precipitation returns to normal.

f) A considerable proportion of Iraq's water resources originate outside its territory (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2014), which makes it considerably vulnerable to the upstream level of water exploitation and development.

g) The upward trends in temperature and potential evapotranspiration, and the downward tendency in precipitation are likely to continue (UNESCO, 2014). The impact of drought is exacerbated by the lack of precipitation (United States Department of Agriculture [USDA], 2008), high demand for water, and increasing human activities. Both the incidence and effects of drought could change in the near future because of climatic alterations and changing vulnerabilities brought on by growing populations and water-using bodies competing over limited water resources (FAO, 2008).

h) Wars and disputes inflamed over the last three decades have dramatically disturbed the socio-economic development plans and considerably delayed the implementation of many water development schemes.

2.8.3 Drought indices

Various approaches have been proposed for identification, quantification and observing of drought episodes. A combination of indicators comprising meteorological, hydrological and other related data resulted in what is called the 'drought index'. Indices make it easier to communicate information about climate anomalies to diverse user audiences and allow scientists to assess quantitatively climate deviations in terms of their intensity, duration, impact area and frequency (Tsakiris & Vangelis, 2005).

Numerous drought indices have been developed such as the Rainfall Anomaly Index (RAI), Percentage of Normal Precipitation (PNPI), Percent of Normal Index (PNI), Deciles Index (DI), Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Reconnaissance Drought Index (RDI), Crop Moisture Index (CMI), Surface Water Supply Index (SWSI), Standardized Precipitation-Evapotranspiration Index (SPEI), Streamflow Drought index (SDI) and Truncation Threshold Level (TTL; also called Drought Threshold Level (DTL)). A list of drought indices, which ranged from a single index parameter such as SPI to more data demanding and time consuming ones such as PDSI, is provided in Keyantash and Dracup (2002) and Institute for Environment and Sustainability (IES, 2008).

The SPI is a precipitation-based index, which has often been applied, in many countries, particularly in recent years (Vincente-Serrano et al., 2004; Wilhite, Svoboda, & Hayes, 2005; Wu et al., 2007; Khadr, Morgenschweis, & Schlenkhoff, 2009; Kumar et al., 2009; Rasheed, 2010; Karavitis et al., 2011; Al-Timimi & Al-Jiboori, 2013; Palchaudhuri & Biswas, 2013; Zarch, Sivakumar, & Sharma, 2014).

Following the Lincoln Declaration on Drought Indices, the experts of the World Meteorological Organization (WMO, 2009b) have reported that the SPI should be used to characterize meteorological droughts by all National Meteorological and Hydrological Services (NMHS) around the world.

The SPI was developed by McKee, Doesken, and Kieist (1993). In its original version, precipitation for a long period at a station is fitted to a gamma probability distribution, which is then required to be transformed into a normal distribution so that the mean SPI value is zero. The index values are then the standardized deviations of the transformed precipitation totals from the mean. The gamma distribution is defined by its frequency or probability density function (Cacciamani et al., 2007):

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \qquad \text{for x > 0} \qquad \text{Equation 2.4}$$

where α and β are the shape and scale parameters, respectively (α and β >0), x is the precipitation amount and $\Gamma(\alpha)$ is the gamma function. The gamma function is defined as:

$$\Gamma(\alpha) = \int_0^{\infty} y^{\alpha-1}\, e^{-y} dy \qquad \text{Equation 2.5}$$

Fitting of the distribution to the data requires the estimation of α and β. Maximum likelihood estimations of α and β are:

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \quad \beta = \frac{\bar{x}}{\alpha} \qquad \text{Equation 2.6}$$

where $A = \ln(\bar{x}) - \frac{1}{n}\sum_{i=1}^{n} \ln(x_i)$ for n observations.

The resulting parameters were then used to find the cumulative probability function $G(x)$ of an observed precipitation event for the given month or any other time scale:

$$G(x) = \int_0^{x} g(x)dx = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \int_0^{x} x^{\alpha-1} e^{-x/\beta} dx \qquad \text{Equation 2.7}$$

Substituting t for $\frac{x}{\beta}$ reduces Equation 2.7 to an incomplete gamma function

$$G(x) = \frac{1}{\Gamma(\alpha)} \int_0^x t^{\alpha-1} e^{-t} dt \quad \text{Equation 2.8}$$

Since, the gamma function is undefined for $x = 0$ and a precipitation distribution may contain zeros, the cumulative probability becomes:

$$H(x) = q + (1-q)G(x) \quad \text{Equation 2.9}$$

where q is the probability of zero precipitation. The cumulative probability $H(x)$ is then transformed into a normal standardized distribution to obtain the SPI index. Positive SPI values denote greater than median precipitation whereas negative values denote less than median precipitation.

The Reconnaissance Drought Index (RDI) is initially based on the ratio of aggregated precipitation to potential evapotranspiration for a certain period (Tsakiris & Vangelis, 2005; Tsakiris, Pangalou, & Vangelis, 2007). Vangelis, Tigkas, and Tsakiris (2013) have indicated that the RDI is more suitable than the SPI for drought severity detection under climate change, because it incorporates precipitation and potential evapotranspiration, the latter being directly related to temperature.

The application of the RDI covers a significant part of many studies that have been conducted for investigating and examining historical droughts in many countries such as Greece (Tigkas, 2008; Vangelis, Spiliotis, & Tsakiris, 2011), Cyprus (Pashiardis & Michaelides, 2008), Malta (Borg, 2009) and Iran (Khalili et al., 2011).

The RDI can be expressed in three forms: the initial form (α_k), the normalized form (RDI_n), and the standardized form (RDIst) (Tigkas, Vangelis, & Tsakiris, 2013). The initial form (α_k) is presented in an aggregated form using a monthly time scale and may be calculated on a monthly, seasonal or annual basis. The α_k can be calculated by the following equation:

$$\alpha_k = \frac{\sum_{j=1}^{j=k} P_j}{\sum_{j=1}^{j=k} PET_j} \qquad \text{Equation 2.10}$$

where P_j and PET_j are the precipitation and potential evapotranspiration of the *j*-month of the hydrological year, respectively. In this paper, *j* = 1 and *j* = 12 for the first and last months of the hydrological year, October and September, respectively.

The second form, the normalized RDI (RDI_n), which represents the deviation from the long-term condition (desirable 30 years) can be computed using the following equation:

$$RDI_n(k) = \frac{\alpha_k}{\bar{\alpha}_k} - 1 \qquad \text{Equation 2.11}$$

where $\bar{\alpha}_k$ is the arithmetic mean of a_k.

The values of α_k follow satisfactorily both the lognormal and the gamma distributions in a wide range of locations and different time scales, in which they were tested (Tigkas, 2008; Tsakiris et al., 2007). In most cases, the gamma distribution was proved to be more successful.

When the lognormal distribution is applied, the RDIst is expressed by the following equation:

$$RDI_{st}(k) = \frac{y_k - \bar{y}_k}{\bar{\sigma}_k} \qquad \text{Equation 2.12}$$

where y_k is the ln(a_k), and $\bar{y}_k$ and $\bar{\sigma}_k$ are its arithmetic mean and its standard deviation, respectively. In the case where the gamma distribution is applied, the RDIst can be calculated following the same procedure as for the calculation of SPI. Concerning the SDI (Nalbantis, 2008), if a time series of monthly streamflow volumes Q_{ij} is available, in which *i* denotes the hydrological year and *j* the month within that hydrological year (j = 1 for October and j = 12 for September), $V_{i,k}$ can be obtained based on Equation 2.13.

$$V_{i,k} = \sum_{j=1}^{3k} Q_{ij} \qquad \text{Equation 2.13}$$

where i = 1,2,…,N, j = 1,2,…,12 and k = 1,2,3,4. $V_{i,k}$ is the cumulative streamflow volume for the i-th hydrological year and the k-th reference period, k = 1 for October-December, k = 2 for October-March, k = 3 for October-June, and k = 4 for October-September. Based on the cumulative streamflow volumes, $V_{i,k}$, the streamflow drought index (SDI) is defined for each reference period k of the i-th hydrological year (Equation 2.14).

$$\mathrm{SDI}_{i,k} = \frac{V_{i,k} - \bar{V}_k}{S_k} \qquad \text{Equation 2.14}$$

where i = 1,2,…,N and k = 1,2,3,4. $\bar{V}_k$ and S_k are the mean and stdev, respectively, of the cumulative streamflow volumes of the reference period k, as these are estimated over a long period of time. In this definition, the truncation level is set to $\bar{V}_k$, although other values based on rational criteria could be also used.

Streamflow may follow a skewed probability distribution, which can be approximated well by the family of the gamma distribution functions. The distribution is then transformed to be normal. Using the two-parameter log-normal distribution (for which the normalization is simply reclaiming the natural logarithms of streamflow), the SDI index is defined in Equations 2.15 and 2.16.

$$\mathrm{SDI}_{i,k} = \frac{y_{i,k} - \bar{y}_k}{s_{y,k}} \qquad \text{Equation 2.15}$$

where i = 1,2,…,N and k = 1, 2, 3, 4 and

$y_{i,k}$ = ln ($V_{i,k}$), i = 1, 2… N and k = 1, 2, 3, 4 Equation 2.16

are the natural logarithms of cumulative streamflow with mean $\bar{y}_k$ and stdev $S_{y,k}$ as these statistics are estimated over a long period of time.

Quantities and descriptive situations of the SDI, SPI and the RDIst indices, which are provided in literature such as (Bonsal & Regier, 2007; Tsakiris et al., 2007; Zarch et al., 2011; Tigkas, Vangelis, & Tsakiris, 2012; Tabari, Nikbakht, & Talaee, 2013) are categorized into seven severity classification groups. These groups are: extremely wet when the drought index is ≥ 2, very wet ($1.5 \leq \text{index} < 2.00$), moderately wet ($1.00 \leq \text{index} < 1.50$), near normal ($-1.00 < \text{index} < 1.00$), moderately dry ($-1.50 < \text{index} \leq -1.00$), severely dry ($-2.00 < \text{index} \leq -1.50$) and extremely dry ($\text{index} \leq 2$).

2.9 Runoff simulation

Runoff is one of the most important hydrologic variables used in most water resources applications. Numerous rainfall-runoff models have been proposed since the mid-1970s. These range from empirical black box through lumped conceptual to more physically-based distributed models. However, the choice of the model depends mainly on availability of reliable and detailed data of watershed characteristics such as soil type and land-use, hydro-meteorologic data such as precipitation and runoff, the time window in which data are available, objectives such as flood peak discharge and annual runoff volume, and the skills of the user. Biased parameters impair the predictive abilities of the models, regardless of the modelling approach used.

Rainfall-runoff models such as NRCS (National Resources Conservation Services) (Zhan & Huang, 2004), HEC-HMS (Hydrologic Engineering Centre-

Hydrologic Modelling System) (Hammouri & El-Naqa, 2007; Yusop, Chan, & Katimon, 2011) and a Mediterranean daily-monthly rainfall-runoff model (Medbasin) (Tigkas & Tsakiris, 2004; Tsakiris et al., 2007; Tigkas et al., 2012) have been widely used to formulate a reliable relationship between rainfall and runoff. Zhang and Savenije (2005) indicated that that there is no universally accepted structure for characterizing the hydrological response directly applicable at basin scale.

The Soil Conservation Services Curve Number (SCS) method (SCS, 1972 cited in USDA, 2004) the former name of the Natural Resources Conservation Service Curve Number method (NRCS) has been widely used to estimate runoff because of its simplicity and applicability with minimum hydrologic information of: soil type, land use and treatment, surface condition, and Antecedent Moisture Condition (AMC) (USDA, 1986; Tigkas & Tsakiris, 2004; Zhan & Huang, 2004; Al-Kadhimi, Ahmed, & Al-Mphergee, 2011; Zakaria et al., 2013).

The method combines the watershed parameters and climatic factors in one factor called the Curve Number (CN). The CN value is a dimensionless empirical index, and has an integer value ranging from 0 (no runoff) to 100 (all rainfall becomes runoff). The CN practical range falls between 40 and 98 (USDA, 1999, 2004). References such as USDA (1986, 1999, 2004) provide detailed guidelines to aid in selecting the appropriate CN values considering the basin characteristics.

A detailed soil and land survey provides the most reliable data, which can be used for estimating the soil storage capacity (S) and obtaining the appropriate CN value. Literature (Pandey & Sahu, 2002; Gandini & Usunoff, 2004; Zhan & Huang, 2004; Gajbhiye & Mishra, 2012) show the use of the Geographic

Information System (GIS) technique worldwide to produce basin-CN maps and estimate the proper CN value. However, essential data are not always available and not simply accessible. The NRCS runoff equation is given in Equation 2.17 (USDA, 2004).

$$Q = \frac{(P-I_a)^2}{(P-I_a)+S_{max}} \quad \text{for } P > I_a \quad \text{and } Q = 0 \text{ for } P \leq I_a \qquad \text{Equation 2.17}$$

where Q is the monthly runoff depth (mm), I_a is the initial abstraction, P is rainfall depth (mm) and S is the storage potential (mm). The maximum soil storage capacity (S_{max}) is given in Equation 2.18 (USDA, 2004).

$$S_{max} = 25.4\left(\frac{1000}{\mathrm{CN}} - 10\right) \qquad \text{Equation 2.18}$$

The original NRCS method assumed the value of the initial abstraction I_a to be equal to 20% of S_{max} (USDA, 2004). The value of 0.2 originally recommended by SCS is now considered by many engineers to be too high for most storm water management situations.

CHAPTER THREE: REPRESENTATIVE CASE STUDY AND METHODOLOGY

3.1 Introduction

Developing a coherent technical framework that can support decision-making for mitigation to and adaptation with the impacts of both, climate change in the basin wide contexts and upstream development requires, a close examination and assessment of the key elements, including but not limited to watershed characteristics, hydro-climatic conditions, human-induced activities, basin development attributes, presence/absence of water agreement between riparian countries, and data availability and accessibility. In order to achieve the objectives and the aim as presented in Figure 1-1, the following list outlines the main components to be covered under the proposed methodology.

1. Identify the data needed
2. Data collection and management
3. Challenges of transboundary waters management
4. Basin development level
5. Unimpaired and impaired flow analysis
6. Impacts of upstream development on lower basin flow regime
7. Analysis of meteorological data
8. Impacts of climate change
9. Baseflow contribution to total runoff
10. Sensitivity of irrigation water demands

3.2 Data

In order to undertake adequate analyses and achieve the objectives and the overarching aim of the thesis, the following list of data is considered important to be gathered whenever possible:

1. Hydrological data such as flow time series, isolated runoff hydrographs, inflows to dams and releases from reservoirs. Various hydrometric stations are targeted.
2. Meteorological data such as precipitation, temperature, humidity, wind speed, sunshine hours, evaporation and potential evapotranspiration. Various meteorological stations are considered.
3. Existing, under construction and planned dams, irrigation schemes, fish farms, water diversion works and public water supply arrangements.
4. Storage capacities of existing, under construction and planned reservoirs
5. Water withdrawals for existing, under construction and planned irrigation projects, fish farms and public water supply practices.
6. Efficiencies of overall irrigation systems.
7. Topographic data including soil type and land use.
8. Groundwater aquifers and their characteristics.
9. Related qualitative documents and data.
10. Geospatial vector data format (shape files) that can spatially describe vector features: points (i.e. water wells), lines (i.e. rivers), and polygons (i.e. lakes).
11. Placemark data files (Google Earth files in kmz or kml formats).

3.3 Description of study area

The topographic extent of the Diyala river basin comprises a drainage area of about 32,600 km^2, of which 43% spans in Iraq and 57% in Iran. Its headwaters originate in Iran; in the Zagros Mountains of western Iran near Hamadān as the Sīrvān river and flowing westwards across lowlands to join the Tigris river in Iraq, south of Baghdad. The basin is situated between 33.216^o and 35.833^o N, and 44.500^o and 46.833^{o}E (Figure 3-1).

The watershed is divided into three main parts: the upper portion drains about 17,900 km^2, accounting for about 55%, the middle segment occupies approximately 11,900 km^2, representing approximately 36% and the lower reach covers nearly 2800 km^2, accounting for nearly 9%. The three parts are heterogeneous in terms of geological and agro-ecological characteristics (Khawer, 2002). The upper and middle portions of the watershed are shared between Iraq and Iran, while the lower segment lies entirely in Iraq. The upper unit of the basin divides into two main sub-basins, Sīrvān and Tanjero. The Sīrvān river drains an area of about 14,600 km^2, including but not limited to three main tributaries: 'Zemkan' river basin occupies a total of 2,600 km^2, out of which 220 km^2 lies in Iraq, 'Gaveh Rood' occupies 2,092 km^2 and 'Gheshlagh' occupies 1,850 km^2 in terms of drainage area. About 25% of the upper unit lies in Iraq while the remaining 75% lies in Iran. The upper part is dammed by series of dams in Iran, whereas, in Iraq it is equipped only by the Derbandikhan dam.

The Tanjero river basin lying entirely in Iraq, whose main tributary is called Chaqchaq (with a catchment area of 253 km^2, total length equal to 42 km and a valley slope of 3%).

The river occupies approximately 3200 km^2. The longest flow path is 90 km and the slope of the valley is 2%. The middle part stretches to the western side of Iran, where headwaters of three main streams are born. These streams descend towards the eastern boundary of Iraq, crossing the borderline and join the middle Diyala reach between Derbandikhan and Hemrin dam. Hemrin dam, located downstream Derbandikhan dam, controls the tail of the intermediate unit in Iraq.

The three main streams are the Havasan, the Qaratu and the AlWand. The Havasan river originates from the western Iranian mountains and joins the main corridor of the Diyala river near 'Maydan village', approximately 38 km downstream of the Derbandikhan dam and about 4 km downstream of 'Maydan bridge'. The river drains about 860 km^2 (Al-Ansari & Al-Jabbari, 1988), out of which approximately 181 km^2, accounting for 21%, is inside Iraq. Its length is 18 km within the Iraqi territories (Khawer, 2002). Concerning the Qaratu river, it stems from the western mountains of Iran and runs along the Iraqi-Iranian borderline for about 38 km. It joins the Diyala river at approximately 60 km downstream of the confluence point between the Havasan and Diyala rivers. The river occupies about 750 km^2 (Al-Ansari & Al-Jabbari, 1988).

Regarding, the AlWand river, it stems from the 'Zagros' mountains within the Iranian side. It flows westwards to pass 'Qaser Shirin' and 'SarPol-e-Zahab' cities in Iran, then heading west to enter the Iraqi border where the city 'Khanaqin' is located. At the end, it pours into the Diyala river at Halwan bridge in 'Sheikh Sa'ad' village. The river basin occupies a total of 3340 km^2, of which 2780 km^2 (83% of the total catchment area) lies in Iran, with the remaining 560 km^2 (17%) in

Iraq. The total length of the river is about 152 km, of which 63 km is in the territory of Iraq (Khawer, 2002).

The climatic conditions vary in that the rainy season covers November to April, while the dry period spans June to September. The long-term minimum, maximum and mean annual precipitations between 1980 and 2010 were about 141 mm, 1087 mm and 459 mm, respectively. The watershed's headwaters in Iran are the main contributors to the streamflow of the upper and middle reaches of the basin. The lower portion of the basin has no discharge signature to the total streamflow. The unimpaired long-term mean daily flow between the water years 1931 and 1961 observed at the most downstream discharge site, is estimated at 173.4 m^3/s, accounting for yearly average runoff of about 5.47 billion m^3.

The headwaters of the basin in Iran are currently densely furnished with a series of dams and hydraulic works. Additional hydraulic structures and inter-basin water transfer tunnels are under construction at the present time and anticipated to be operational in 2018. Some other hydraulic facilities are currently under study or at the planning stage. The main river corridor in Iraq is equipped with two main dams (Derbandikhan and Hemrin) and the Diyala weir. The Diyala weir is a fully controlled barrage across the head of the lower Diyala plain. This hydraulic complex ensures two-way water diversions for irrigation, the combined canal (As Sadder El-Mushtarak canal) on the right bank and the Al-Khalis canal on the left bank. The entire basin is agriculturally highly developed.

The agriculture sector nowadays represents the largest water consumer of the annual water withdrawals, in particular in the upper and middle parts of the basin in Iran, and in the lower portion in Iraq. The lower riparian actor has been wrestling, in particular since 1999, with the combined effect of basin-wide successive and extended droughts and massive water abstraction schemes upstream.

A set of existing pumps located on the left bank of the Tigris river in Iraq is currently used to transfer about 288 million m^3 of water annually from the Tigris river to the Diyala basin to compensate for the water shortage of the lower reach of the basin. Moreover, a recommendation was made, yet has not been implemented, to transfer the water from the Lesser Zab river in Iraq to the Diyala basin via the Lesser Zab-Diyala proposed link canal (Harza & Binnie, 1963). The recommended mean annual flow volume was estimated at 945.4 million m^3 (Ministry of Water Resources [MoWR], 1982b).

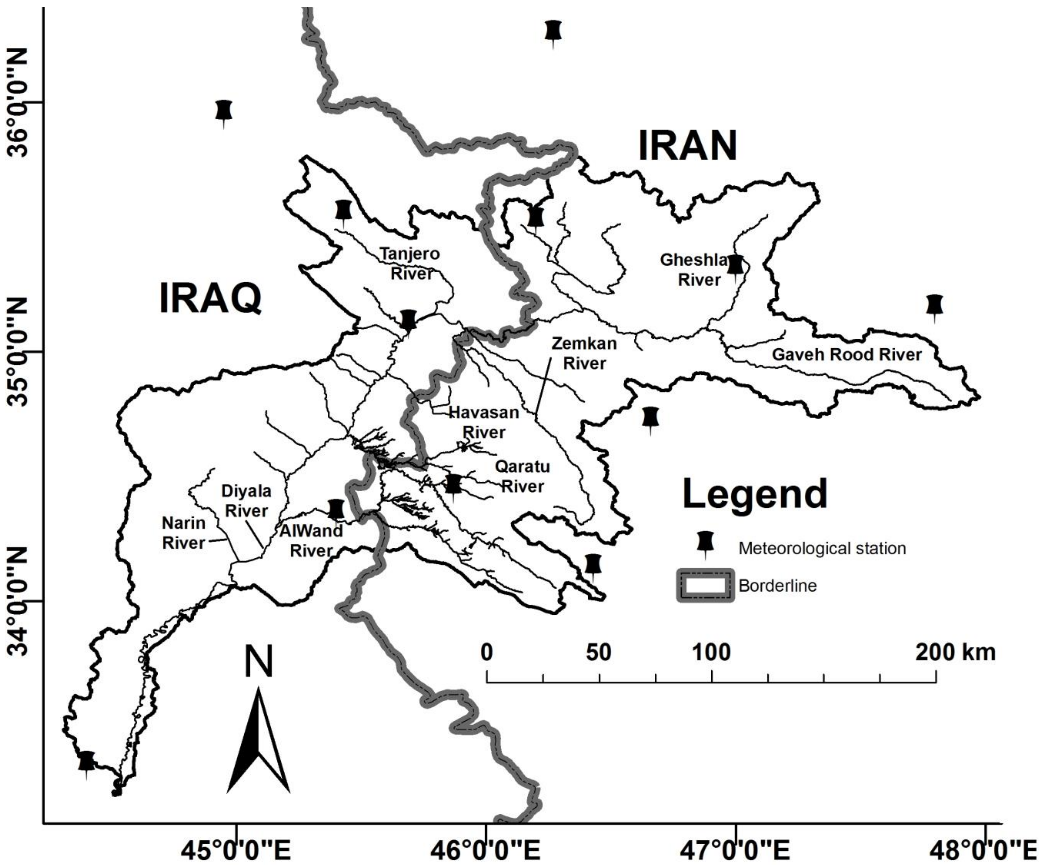

Figure 3-1: Diyala basin and the distribution of meteorological stations.

3.4 Data collection and management

3.4.1 Collected data

The gathered data are categorized into five main groups. These groups are: flow records, meteorological parameters, hydraulic structures such as dams, irrigation and water abstraction, and other useful data such as Google kmz/kml and shape files.

Flow data: Four flow time series were collected. These encompass: (a) daily flows between 1955 and 2013 observed at the Derbandikhan hydrometric site (DHS) in Iraq. The drainage area at this site is estimated at about 17,900 km^2 (b) daily flows between 1931 and 1961 observed at the Diyala discharge site (DDS) in Iraq. The catchment at this site occupies a drainage area of approximately 29,800 km^2 (c) monthly flow data at the DDS between 1925 and 1961 and (d) monthly side flow for the middle portion of the basin between 1931 and 1961. The coordinates of the DHS and the DDS are 35.11°N and 45.70°E and 34.10°N and 44.97°E, respectively (Figure 3-2). No missing records were attended in all available time series. The data were obtained from various sources (Harza & Binnie, 1958, 1959, 1963; United States Geological Survey [USGS], 2010; Ministry of Agriculture and Water Resources in Kurdistan- Regional Government of Iraq [MoAgWR-KRG], 2013, unpublished data).

Meteorological data: Meteorological data such as precipitation and mean air temperature were gathered. The data includes monthly precipitation and mean air temperature data from 12 meteorological stations (Figure 3-1) of altitudes ranging from 32 masl to as much as 1906 masl within and in close proximity to the basin examined for the period between 1962 and 2010. Data were acquired from various sources such as the MoAgWR-KRG and the Iranian Meteorological Organization (IMO). Some other meteorological data in Iraq were obtained from the FAO (2004). In addition 67 grid climate data of altitudes ranging from 34 masl to as much as 2736 masl within and in close proximity to the basin were examined. Interpolated daily climatic data such as precipitation (P), minimum (Tmin), maximum (Tmax), mean air temperatures (Tmean), radiation and humidity between 1980 and 2010 were made available from the National Centres for Environmental Prediction (NCEP), Climate Forecast System Reanalysis (CFSR; Retrieved 05 August, 2014 from http://globalweather.tamu.edu/home/). The data were used to fill up some missing records observed at some of the 12 meteorological stations.

Hydraulic structures: Data on existing and under construction dams including the storage capacities and the time lines in which the hydraulic works were operated or projected to be put in place were collected. Table 3-1 and Figure 3-2 summarizes the damming of the main river corridor and its headwaters between 1983 and 2018.

Irrigation and water withdrawals: Data on existing, under construction and under study/planned water withdrawals schemes including the areas of the projects, current and projected total irrigation water requirements (TIWR) were gathered. Data also include the periods in which the projects were put online or planned to be accomplished. The data were obtained from various sources (MoWR, 1982a,b, 2008, 2010a,b; Khawer, 2002; Aliasghari & Ahadi, 2007; Mahabghodss.com, 2008, 2013; Isdle.ir, 2009; Jafari et al., 2009; Tokmechi, 2011; Zagonari, 2011; Asadi, Ghaderzadeh & Seirafi, 2012; Salimeh, 2012; Crea, 2013; Jtma.ir, 2013; Jyane.ir, 2013; Pooyab.org, 2013; Sadafzar.ir, 2013).

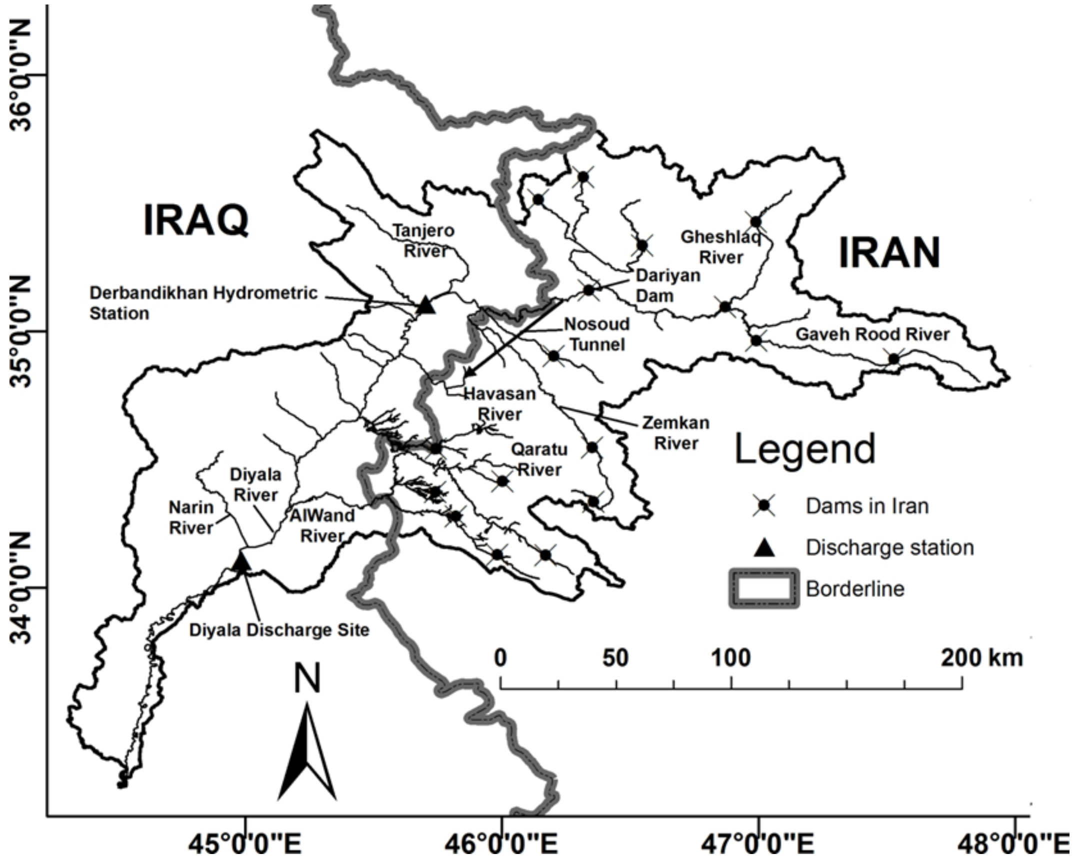

Figure 3-2: Diyala basin, discharges sites, hydraulic structures and inter-basin water transfer scheme.

Table 3-2 and Table 3-3 are developed to summarize the targeted irrigation arrangements for the Diyala basin in Iraq (MoWR, 1982a,b, 2008, 2010a,b) and the targeted water abstraction for the Diyala basin in Iran, respectively. A schematic diagram is developed to illustrate the water withdrawals schemes (Figure 3-3).

Other useful data: Some useful Google kmz/kml and shape files were obtained from the database of Global Administrative Areas (GADM, 2012).

Unavailable or inaccessible data: Unavailable or inaccessible data are the cropping pattern, the cropping intensity, the irrigation system performance efficiency, groundwater aquifers, and the characteristics of the agro-ecological zone (AEZ) areas in which the irrigation projects are situated.

Table 3-1: Damming of main river corridor and its headwaters and inter-basin water transfer scheme in Iran between 1983 and 2018.

Year	No. of dams	Storage capacity (mcm)	Acc. Storage capacity (mcm)	Year	No. of dams	Storage capacity (mcm)	Acc. storage capacity (mcm)
1983	1	224	224	1999	N/A	N/A	321
1984	N/A	N/A	224	2000	N/A	N/A	321
1985	N/A	N/A	224	2001	N/A	N/A	321
1986	N/A	N/A	224	2002	N/A	N/A	321
1987	N/A	N/A	224	2003	N/A	N/A	321
1988	N/A	N/A	224	2004	1	550	871
1989	N/A	N/A	224	2005	N/A	N/A	871
1990	N/A	N/A	224	2006	1	52	923
1991	N/A	N/A	224	2007	N/A	N/A	923
1992	N/A	N/A	224	2008	N/A	N/A	923
1993	N/A	N/A	224	2009	N/A	N/A	923
1994	1	97	321	2010	N/A	N/A	923
1995	N/A	N/A	321	2011	1	70.5	993.5
1996	N/A	N/A	321	2012	3	470.1	1463.6
1997	N/A	N/A	321	2013	1	300	1763.6
1998	N/A	N/A	321	Total	9		
N/A means no dam was put in place in the corresponding year, mcm: Million m^3, Acc.: Accumulated							
Daryan dam: Expected to be put in place in 2018: Total capacity 316 mcm. 281 mcm active capacity. Surface area of 10 km^2 with a maximum width of 800 m. The dam is currently under construction (see Figure 3-2).							
Nosoud tunnel: Expected to be commissioned in 2018: 70 m^3/s (design discharge). To supply 1378 mcm/year to irrigate areas in south-western Iran. The tunnel is currently under construction (see Figure 3-2).							

Table 3-2: Targeted irrigation arrangements for Diyala basin in Iraq (MoWR, 1982a,b, 2008, 2010a,b [see Figure 3-3]).

Sub-basin	Project	Total net irrigation area (ha)	Current net irrigation area (ha)	Total annual IWR (mcm)	Current annual allocated water (mcm)
Upper Diyala	1. Shahrazur	11,250	0	88	0
	2. Kaolas	6,450	645	26	3
	3. Small farms in Sulaimaniya at springs	13,550	10,840	183	146
	4. Qara Ali	5,536	830	60	9
	Subtotal	36,786	12,315	357	158
Middle Diyala	1. Sheikh-Langar	6,850	3,699	43	23
	2. Balajo-Khanaqin-AlWand	20,000	17,188	149	128
	3. Qara-Tappa	17,500	15,750	150	135
	4. Jalawla	3,000	2,700	28	25
	5. As-Sa'adiyah	7,100	5,680	71	57
	6. Kalar	3,750	2,250	8	5
	7. Bawanur	11,250	0	82	0
	8. Small farms at wells	1,790	1,074	52	31
	Subtotal	71,240	48,341	584	405
Lower Diyala	1. Upper khalis	61,500	43,050	637	446
	2. Lower Khalis	57,500	57,500	719	719
	3. Mandeli	7,750	1,590	121	25
	4. Haruniyah and AsSudour	14,175	14,175	86	86
	6. Ruz	57,500	57,500	592	592
	7. Muqdadiyah	7,000	7,000	87	87
	8. Mahrut	41,750	9,250	464	102
	9. Khoraissan	23,795	14,277	237	142
	10. Sariya-Tel-Asmar	40,500	24,300	422	253
	11. Small farms in lower course along the right bank	3,751	2,251	72	43
	12. AnNahrawan	12,900	7,740	194	116
	13. Small farms from the boundary of AnNahrawan to the mouth of the river	8,451	5,071	157	94
	Subtotal	336,572	243,703	3,788	2,707
	Total	444,598	304,359	4,729	3,270
ha: Hectare, mcm: Million m^3, IWR: Irrigation water requirements					

Table 3-3: Targeted water abstraction for Diyala basin in Iran (see Figure 3-3).

Sub-basin in Iran	Project	Project ID	Area (ha)	Annual TIWR (mcm)
Upper Diyala	Irrigation	1a	3,768	23
	Fish farm	1b	10	0
	Irrigation	2a	2,200	13
	Fish farm	2b	800	15
	Irrigation	3a	31,000	189
	Domestic	3b	N/A	63
	Irrigation	4a	5,800	35
	Domestic	4b	N/A	7
	Irrigation	5	4,200	26
	Irrigation	6	3,850	23
	Irrigation	7	N/A	260
	Irrigation	8a	12,000	73
	Domestic and industrial	8b	N/A	23
	Irrigation	9	19,100	117
Sub-total			82,728	867
Middle Diyala	Irrigation	10	18,000	148
	Irrigation	11	3,600	30
	Irrigation	12	6,500	54
	Irrigation	13	4,200	35
	Irrigation	14	3,150	26
	Fish farm	15	5,200	129
	Irrigation	16a	8,300	68
	Domestic	16b	N/A	15
	Irrigation	17	4,830	40
Sub-total			53,780	544
Total			136,508	1,411
ha: Hectare, mcm: Million m^3, TIWR: Total irrigation water requirements				

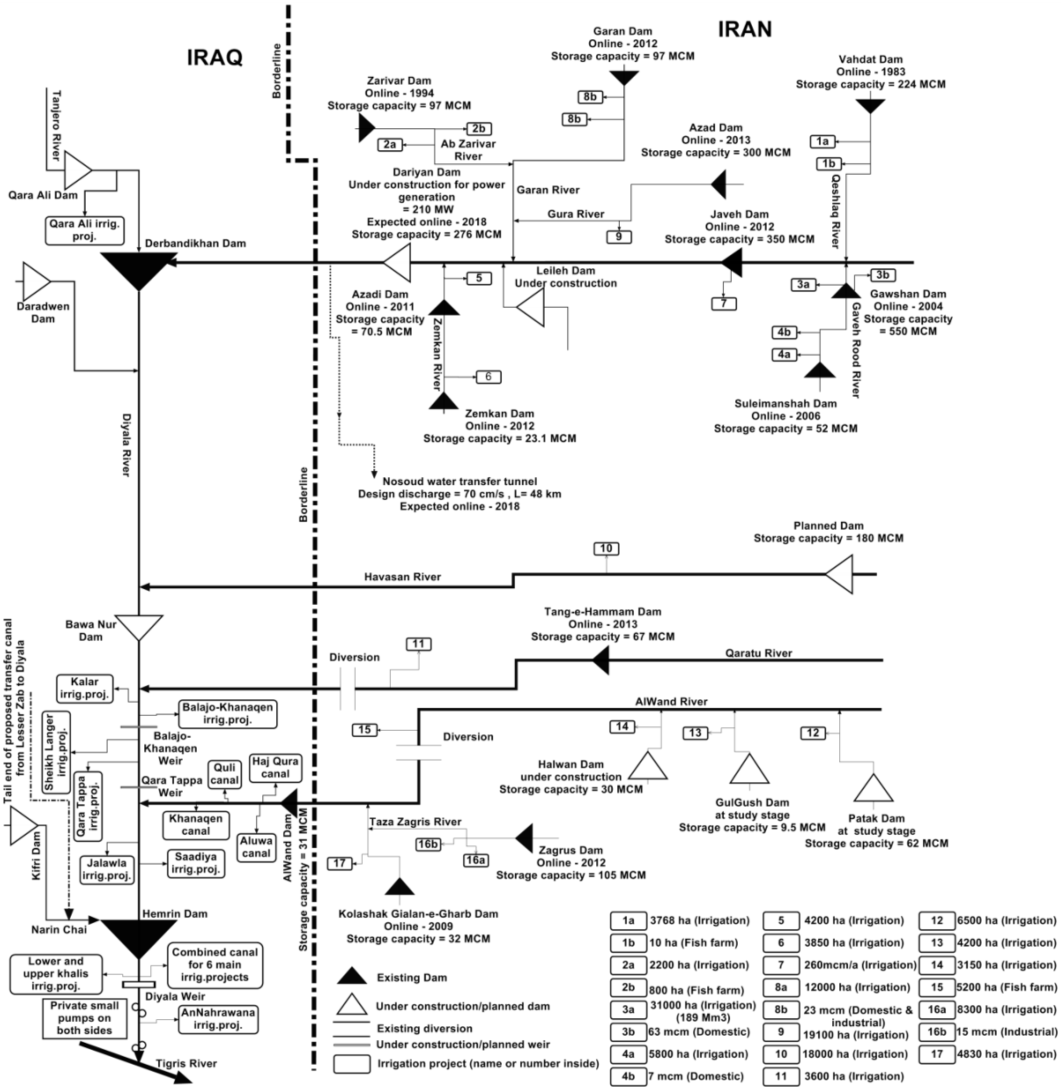

Figure 3-3: A schematic diagram for river damming and water exploitation schemes on Diyala basin.

3.4.2 Data storage systems

Data of various formats such as spread sheets, word documents and scanned papers were collected, which were either provided by official sources, drawn from published documents or downloaded from websites. In some cases, it was necessary to translate documents from Kurdish and Persian languages to English. In this research, the HEC-DSSVue (HEC Data Storage System Visual Utility Engine) version 2.01 of the United States Army Corps of Engineers (USACE)-HEC was used to comprehensively develop a database for achieving and processing the data. The Microsoft Excel add-in associated with the HEC-DSSVue was used to retrieve and store data directly from the spread sheet files. Moreover, a geodatabase was developed for spatial data storage and management for ArcGIS application.

3.5 Methods

3.5.1 Descriptive statistics of flow and meteorological data

Magnitude and timing of river flow time series under natural and artificially influenced flow conditions are assessed. In this thesis, quantitative statistical descriptors such as mean, median, standard deviation and percentiles, and visual presentations are used to assess the flow characteristics and variability. As far as meteorological data are concerned, descriptive statistics such as minimum, mean, maximum and standard deviation are used to describe the basic features of the data. The homogeneity test (double-mass curve) (Eris & Agiralioglu, 2012) is applied as an essential tool to account for changes in data collection procedures (or other local conditions) and examine the consistency of the precipitation data available at the investigated meteorological stations. The detection of trends in precipitation, temperature and potential evapotranspiration time series is performed using the non-parametric Mann-Kendall (M-K) test (Hisdal et al., 2001; Helsel & Hirsch, 2002; Wu et al., 2008) at 5% significance level. The software XLSTAT 2013.5 is used to accomplish the analysis. The M-K test has often been applied in many previous studies (Kahya & Kalayci, 2004; Gadgil & Dhorde, 2005; Li et al., 2008; Yaning et al., 2009).

The limited access to a wide range of meteorological data such as minimum and maximum air temperature, minimum and maximum relative humidity, solar radiation, and wind speed has led to the use of a temperature-based method (Blaney-Criddle (B-C)) for estimating the potential evapotranspiration (PET). Moreover, the use of the B-C method is appropriate for the calculation of the RDI (Vangelis et al., 2013). The application of the B-C procedure has also been proven to be a reliable method for both different locations and climates worldwide (Fooladmand & Ahmadi, 2009; Benli et al., 2010; Mohawesh, 2010; Razzaghi & Sepaskhah, 2010; Fooladmand, 2011). The DrinC software (Tigkas et al., 2013; Tigkas, Vangelis, & Tsakiris, 2014) is utilized to determine the PET. The default value (average of 0.85) for the crop coefficient is used in the computation process.

3.5.2 Transboundary three-geographical scales

This section has been published in the following journal:

Al-Faraj, F. A. M., & Scholz, M. (2014b). Impact of upstream anthropogenic river regulation on downstream water availability in transboundary river watersheds. *International Journal of Water Resources Develop*ment. doi: 10.1080/07900627.2014.924395

This section aims at providing a viable analytical, planning and management platform for sustainable utilization of shared water resources. The transboundary three-scalar conceptualized platform is constructed as a support concept to assessing the potential impact of disparity in interests and actions between or among two or more riparian actors sharing the same watershed. The conceptualized platform highlights challenges related to management of transboundary waters and brings into focus the major components, placing them in the context of the transboundary scale (sharing responsibilities, sharing risks and sharing benefits).

Fundamentally, this is a response to the much-criticized, unilateral nation-based approach to water management, underlining instead the advantages that a holistic approach to water governance, on a catchment-based integrated approach, can offer.

3.5.3 Assessment of the hydrologic alterations

The new approach presented in this section has been published in the following journal:

Al-Faraj, F. A. M., & Scholz, M. (2014a). Assessment of temporal hydrologic anomalies coupled with drought impact for a transboundary river flow regime. The Diyala watershed case study. *Journal of Hydrology*, *517*, 64-73.

This section aims at assessing the collective impact of upstream anthropogenic interventions and climate change in the transboundary context on the flow regime condition of the lower riparian country. The Indicators of Hydrologic Alteration (IHA) software version 7.1 (Richter et al., 1996) and the HEC-DSSVue are used. A subset of the IHA indices is utilized in assessing the extent to which the natural flow regime has been deviated. The successive drought periods are also considered in this analysis.

The indices that are used are: the annual and monthly mean flows, monthly and annual medians, and magnitudes of annual extreme conditions such as the 1-, 3-, 7-, 30-, and 90-days minima and maxima. Lower and upper thresholds of percentiles such as the 10th, 25th, 50th, 75th, and 90th percentiles are also considered. The calculated hydrologic statistical indicators are further validated through temporal comparisons with all forms of regulation observed along the main river corridor and its headwaters in the upstream country.

The analysis considers daily flow data between 1955 and 2013 observed at the DHS. The year 1983, in which the first hydrologic alteration occurred, is considered as a reference timeline. The entire time series is divided into two main groups: unregulated and regulated periods. The water years between 1955 and 1982 represent the pre-regulation condition, while the post-regulation condition covers the hydrologic years 1983-2013. The natural flow regime (pre-regulation condition) is chosen as a reference condition (benchmark) to which the characteristics of the post-impacted time series are compared.

Three time intervals are identified for the post-regulation time scale. These time scales depend on the degree of human intervention such as damming and increased water withdrawals. The three artificially impaired time intervals were as follows: 1983-2013, representing the entire period since the year when the first dam was commissioned; 1999-2013, characterized by drought spells (1999-2001 and 2008-2009) coupled with intensive artificial regulation since 2004; and 2004-2013, reflecting the years in which remarkable damming, diversion and water withdrawals were put in place combined with drought events (2008-2009).

The application of the IHA model is not limited to quantifying the artificial hydrologic alteration, but can further identify the temporal changes in the cumulative hydrologic anomaly due to annual climatic conditions and increases in upstream human activities altering watercourses and landscapes.

3.5.4 Sensitivity analysis of surface runoff

The new approach presented in this section has been published in the paper shown below:

Al-Faraj, F. A. M., Scholz, M., & Tigkas, D. (2014d). Sensitivity of surface runoff to drought and climate change: Application for shared river basins. *Water, 6*(1), 3033-3048.

This section aims at assessing the anticipated drought and climate change at river basin scale on streamflow availability for the lower riparian state. This is achieved through a combined use of a wide range of changes in the amount of precipitation (P) (a decline between 0 and −40%) and in the potential evapotranspiration (PET) (an increase between 0 and +30%), and the Medbasin-M rainfall-runoff model. The Medbasin-M is calibrated using the monthly P and PET data for the period of 12 hydrologic years (1962-1973) for which unimpaired streamflow data are observed and used for model calibration.

The simulation results are validated using monthly climatic data (P and PET) and the unregulated observed runoff for a period of nine water years (1974-1982). The Blaney-Criddle method (Doorenbos & Pruitt, 1977 cited in Hamid, 2011) is used to estimate the PET values, with the DrinC software being run for such calculations (Tigkas et al., 2013, 2014).

The model uses three calibration parameters. These are the maximum soil storage capacity (Smax), the coefficient of the deep percolation (C) and the monthly delay factor (a), which is used to adjust the monthly runoff distribution (Giakoumakis, Dercas, & Karantounias, 2005). The required input data for the model are monthly P and PET data.

A detailed soil and land survey provides the most reliable data, which can be used for estimating the soil storage capacity (S) and obtaining the runoff curve number (CN) as part of the model requirements. However, essential data are not always available and not simply accessible. For this study, the maximum soil storage capacity (Smax) was estimated using Equation 2.18, which was developed by the Natural Resources Conservation Service (NRCS, formerly known as the Soil Conservation Service), which relates Smax to CN (SCS, 1972 cited in USDA, 2004).

The runoff curve number is an empirical parameter, which is mainly a function of the hydrologic soil group, cover type, treatment, hydrologic condition and antecedent runoff condition. References such as USDA (1986, 1999, 2004) provided detailed guidelines to aid in selecting the appropriate CN values considering the basin characteristics. The CN is an alternative way to estimate the model's parameter Smax. However, in this study, no sufficient and reliable information such as land use and soil types are available or accessible to be used for the calculation of the CN. Therefore, Smax was calculated through a model calibration process.

Initial values of CN and C are first assumed. A two-stage process is conducted for the calibration of the model parameters. The first stage involves matching the volumes of observed and simulated hydrographs on an annual basis. In the second stage, the shape of the simulated hydrograph is compared with the shape of the observed hydrograph. A trial and error approach is utilized until the best fit is achieved.

Some statistical goodness-of-fit tools are employed for calibrating the model and validating the simulation results. These measures are correlation coefficient (r) (Legates & McCabe, 1999; Krause, Boyle, & Base, 2005), the root mean squared error (RMSE) (Reusser et al., 2009), the mean absolute error (MAE) (Reusser et al., 2009) and the index of agreement (IoA) (Legates & McCabe, 1999; Krause et al., 2005). Equations 3.1 to 3.4 show the formulas applied for the goodness of fit tools, respectively.

$$r=\sqrt{\frac{\sum_{i=1}^{n}[(R_{obs})_i-\bar{R}_{obs}][(R_{obs})_i-\bar{R}_{sim}]}{\{\sum_{i=1}^{n}[(R_{obs})_i-\bar{R}_{obs}]\}^{0.5}\{\sum_{i=1}^{n}[(R_{sim})_i-\bar{R}_{sim}]\}^{0.5}}} \quad \text{Equation 3.1}$$

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}[(R_{obs})_i-(R_{sim})_i]^2} \quad \text{Equation 3.2}$$

$$MAE=\frac{1}{n}\sum_{i=1}^{n}|(R_{obs})_i-(R_{sim})_i| \quad \text{Equation 3.3}$$

$$I_oA=1-\frac{\sum_{i=1}^{n}[(R_{obs})_i-(R_{sim})_i]^2}{\sum_{i=1}^{n}[|(R_{obs})_i-\bar{R}_{obs}|+|(R_{sim})_i-\bar{R}_{obs}|]^2} \quad \text{Equation 3.4}$$

where R_{obs}, R_{sim}, $\bar{R}_{obs}$ and $\bar{R}_{sim}$ are the observed runoff, simulated runoff, and means of the observed and simulated runoffs, respectively. N is the number of years and *i* is the time step.

The annual Standardized Reconnaissance Drought Index (RDIst) and Streamflow Drought Index (SDI) indices are computed using the DrinC software (Tigkas et al., 2013, 2014) over the period of the normal climatic period from 1975 to 1982. The precipitation and runoff data are fitted to the log-normal distribution function in the computation process. Finally, the RDIst and SDI nomographs are developed, which describe the ‘departure’ from the normal condition based on the

‘0 scenario’. The reference mean annual runoff volume indicating the condition of zero-change in both P and PET is referred to as the ‘0 scenario’.

The RDIst values are calculated over a time window of 30-years between 1962 and 1991. This is performed to specify which period represents nearly the normal climatic condition (on average). The period of nearly normal climatic condition expresses the timeframe in which no extreme RDIst values are observed and when on average the RDIst value is close to zero. The period of eight water years (1975 to 1982), which characterized the normal condition, is used for running the climatic scenarios. Moreover, the period between 1975 and 1982 was devoid of any considerable human construction activities (e.g., hydraulic control structures and large-scale irrigation schemes) in the upstream country Iran.

The Medbasin-M model is used to compute the reference mean annual runoff for the normal climatic condition. The synthetic scenarios for assessing the runoff sensitivity to climate change were formulated through an incremental shift of the historical P and PET values by a 2% step for a P reduction range from 0 to −40% and a PET increase from 0 to +30%. Correspondingly, 336 scenarios were developed representing the mutual impact of deviations in P and PET values that lie within the aforementioned assortment of scenarios. These scenarios include all possible basin-wide climate change projections as well as a wide array of drought severity conditions. The Medbasin-M model is repetitively used to simulate the runoff for the 336 scenarios.

3.5.5 Development of national drought policy in climate alterations

This section has been published in the following journal:

Al-Faraj, F. A. M., Scholz, M., Tigkas, D., & Boni, M. (2014e). Drought indices supporting drought management in transboundary watersheds subject to climate alterations. *Journal of Water Policy*. doi: 10.2166/wp.2014.237

This section aims at bridging the knowledge gap between the drought impact and the nation-wide policy formulation, assisting decision-makers and planners in the Diyala basin and other similar transboundary watersheds to develop water resources management strategies in the context of drought. Two commonly used drought indices (SPI and RDI) are applied to explore the dynamics of the historical meteorological drought episodes in the examined basin, through reconstruction of historical drought incidences. The monthly observed precipitations and mean air temperatures data between the hydrologic years 1980 and 2010 are analysed. The B-C method is used for estimating the potential evapotranspiration (PET).

3.5.6 Estimation of baseflow contribution to total runoff

This section has been published in the following journal:

Al-Faraj, F. A. M., & Scholz, M. (2014c). Incorporation of the flow duration curve method within digital filtering algorithms to estimate the base flow contribution to total runoff. *Journal of Water Resources Management*. doi: 10.1007/s11269-014-0816-7

This section aims at managing groundwater as part of a transboundary sustainable integrated approach that includes surface water and water conservation. Availability of surface water, particularly for the lower riparian states is challenged by climate change and human-induced intrusions at the upper country, which increases pressure on groundwater. Moreover, proper estimation of baseflow contribution to total runoff is central to avoiding overdraft use of groundwater and aquifers depletion.

Two of the widely used digital filtering algorithms (Equations 2.1 and 2.2) and the FDC method are applied. The following generic methodology is proposed to overcome the shortcomings of the digital filtering algorithms such as the need for groundwater data, aquifer characteristics and isolated storm hydrographs. The outcomes of the flow duration curve analysis are incorporated into two one-parameter digital filtering algorithms to obtain the value of the filter parameter, and appropriately identify the temporal changes of the baseflow contribution. The process of computation is described in the following five steps:

1. The frequency duration curve is developed using the daily runoff records. Two time series are used: (a) daily flows at the DHS between 1955 and 1982 (b) daily flows at the DDS between 1931 and 1961. The two time series represent the natural flow regime. Q90 and Q50 are determined to calculate Q90/Q50, which is referred to as the long-term mean annual proportion of the total runoff from groundwater storage and other delayed flow sources or the long-term mean annual percentage of the BFI.
2. The FDC method is combined with the one-parameter digital filtering algorithm technique. The data are filtered for various values of filter parameter α until the BFI becomes equal to Q90/Q50. Filtering is started with the default value of α equal to 0.925. The obtained separated baseflow is constrained so that it is not negative or greater than the total runoff in any time step. This implies that if the calculated q_t is less than zero, then $q_t = zero$, and if $q_t > Q_t$, then $q_t = Q_t$, otherwise $q_b = Q_t - q_t$. The α value by

which the above mentioned condition is achieved represents the optimal value in the digital filtering algorithm that can be used in the next step to obtain a time series of baseflow for a specific time step (i.e. day, month or year).

3. Three time series of daily, monthly and annual baseflow are computed using the optimal value of α obtained in step 2.
4. A linear regression analysis is conducted between the annual BFI and the annual runoff to gauge whether wet or dry years had a tendency to give rise to low or high BFI values. The coefficient of variation of annual BFI is performed for stability verification purposes. The definition of dry and wet years is based on the 25th and 75th percentiles, respectively. The years for which the mean annual runoffs are below the 25th percentile are considered as dry years, while those with mean annual runoffs greater than the 75th percentile are considered to be wet years.
5. The cyclic analysis to reflect the seasonal variability of BFI for wet and dry periods is performed using the HEC-DSSVue. Two daily BFI time series, which represent the wet season (February to May) and dry season (June to September), are extracted from the computed daily BFI (see item 3). The cyclic analyses are performed for the two extracted datasets (wet and dry periods). Seven time series are obtained, which represent the minimum, mean, median and maximum values as well as the 10th, 25th and 75th percentiles.

3.5.7 Isolating the effect of climate change and human activities on surface runoff

This section has been submitted to the following journal:

Al-Faraj, F., & Scholz, M. Impact of basin-wide dry climate conditions and non-climatic drivers: an isolation approach. *Journal of Water and Climate Change* (under consideration).

This section aims at partitioning the impacts of climate change at basin-wide scale and upstream human activities on surface runoff available for the downstream country. The new generic statistical methodology provides a solid platform for understanding the proximate and root causes of reduction in water resources and support water resources management and sustainable development under the mutual influence of climate change and man-made activities.

The following steps describe the application of the new proposed methodology to the Diyala watershed.

1. For the pre-regulation monthly mean extended streamflow time series (1925-1982):
    a. The flow duration curve analysis (FDCA) is conducted for the 58-year unimpaired monthly mean flow time series observed at the DHS to determine the monthly-based truncation levels at 70%. The HEC-DSSVue and the HEC-SSP are applied for the FDCA. Twelve monthly truncation levels are extracted (i.e. one threshold value per month).
    b. For each month, the monthly mean stream flows, which are less than the corresponding monthly-based truncation level (calculated in step 1a), are marked.

c. The ratios between the marked streamflow values in step 1b and their corresponding monthly-based truncation level as obtained in step 1a are calculated. For each month, the standard deviation of the calculated ratios is determined.

2. For the post-regulation monthly mean streamflow time series (1983-2013):

a. The same process as described in step 1b is followed.

b. The process as outlined in step 1c is repeated.

c. The ratios between the standard deviation values computed in step 1c and the ones determined in step 2b are estimated to isolate the proportion of impact of the upstream artificial regulation from the mutual impacts of upstream anthropogenic pressures and basin-wide dry climate conditions.

d. Finally, the monthly proportion of the impact of the upstream artificial regulation equals the value obtained by the following simple calculation: 1–(ratio calculated in item 2c) ×100.

3.5.8 Sensitivity of irrigation water requirements to irrigation system improvements

This section has been accepted for the 9th World Congress of the European Water Resources Association (EWRA), which will be held in Istanbul, Turkey between 10 and 13 June 2015.

This section aims at quantitatively assessing the rate of change in TIWR through improved management of irrigation supplies. The synthetic scenarios for judging the sensitivity of the TIWR to ISP_{Eff} improvements are formulated through an incremental growing of the ISP_{Eff} value by a 2% step for a range from 40% to

60%. Correspondingly, 10 scenarios are developed. The range of ISP_{Eff} is chosen considering that the change for better ISP_{Eff} is a very slow and challenging process. Various factors have an impact on the evolution of the ISP_{Eff} such as the current ISP_{Eff} (2014-level ISP_{Eff}), existence of a clear programme to improve the infrastructure for irrigation projects, allocation of sufficient funds, determination of the timeframe for implementation, existence of a continuous maintenance programme and the level of water scarcity.

Considering, the inter-basin water transfer systems and irrigation area development in Iraq, five potential scenarios have been developed. These scenarios are illustrated in Figure 3-4. The first scenario (S1) assumes no further development of irrigation area on the Diyala basin in Iraq (present-day level) and maintains the annual current contribution of the Tigris river of approximately 288 million m^3. This scenario appears pessimistic, however, the main justifications for its consideration are: the part of the basin in Iraq is presently considered as an inflamed conflicts area, most of the infrastructures for the irrigation systems are deteriorated and inefficient, and the area is socio-economically unstable.

The second scenario (S2) takes the targeted irrigation area into account, and sustains the present-day involvement of the Tigris river, through supplying about 288 million m^3/year. This scenario is hard to achieve, though it has been considered to bring about optimal use of water and minimize irrigation water losses. The third scenario (S3) considers the targeted irrigation area associated with annual compensation from Tigris and Lesser Zab rivers of 1233 million m^3. This scenario sounds achievable, yet it depends mainly on the implementation of the Lesser Zab-

Diyala inter-basin water transfer project and the level of development in irrigation efficiency.

The last two scenarios (S4 and S5) adopt 50% (about 473 million m^3) and 100% (approximately 946 million m^3) of Lesser Zab contributions, respectively. Moreover, they assume no contribution from the Tigris river and consider the targeted irrigation area. The time window 2030-2035 has been chosen as the potential projected time span during which partial improvement or the targeted figure is anticipated to be attained.

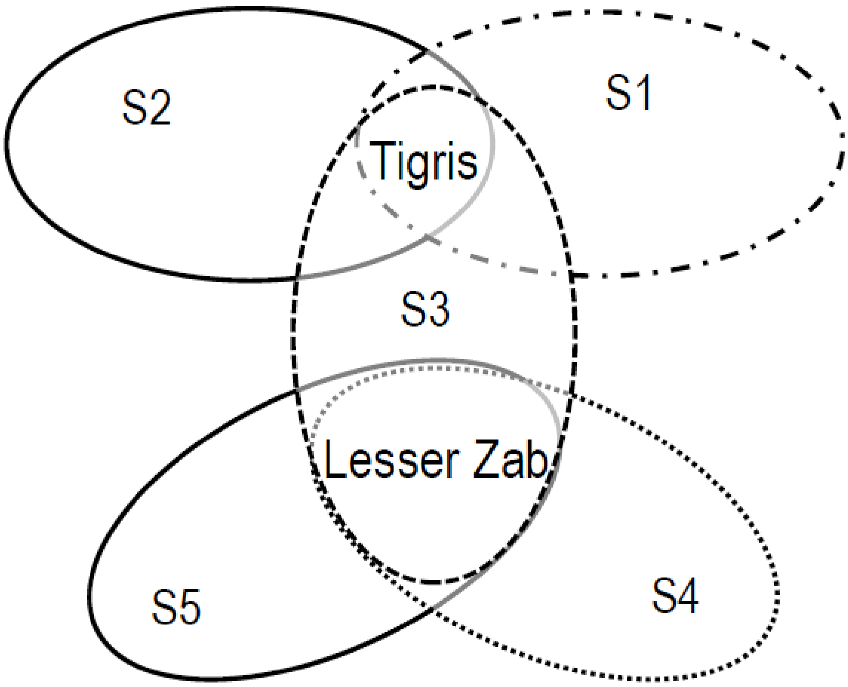

Figure 3-4: Potential scenarios for the Diyala basin in Iraq.

3.5.9 Formulation of adaptation and mitigation measures

This section aims at formulating a generic process through which adaptation and mitigation measures to handle, cope with and alleviate the likely adverse mutual implications of climate change at transboundary level and upstream human-induced perturbations can be explored. Given that transboundary water management is growing progressively more difficult, a proper consideration of the magnitude of challenges and key components will enable the presentation of adaptation and mitigation measures in a meaningful and understandable way.

Figure 3-5 presents a process, which encompasses six key components, including actions to be undertaken at national and transboundary contexts, to limit the magnitude and/or rate of the combined impact. The measures should be adjusted to effectively fit the specific basin-wide characteristics and needs.

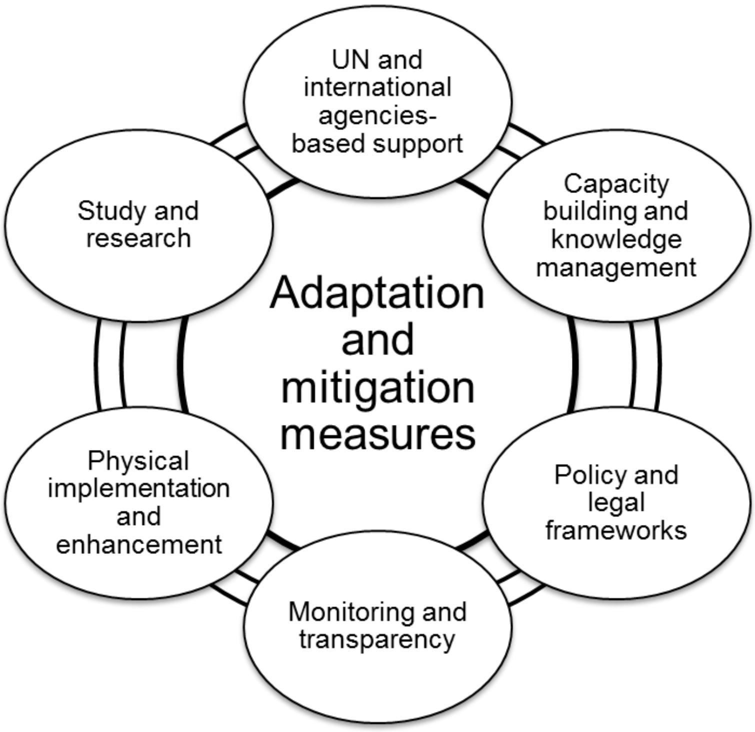

Figure 3-5: Proposed process for generic adaptation and mitigation measures.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Transboundary three-geographical scales

This section has been published in the paper shown below:

Al-Faraj, F. A. M., & Scholz, M. (2014b). Impact of upstream anthropogenic river regulation on downstream water availability in transboundary river watersheds. *International Journal of Water Resources Development*. doi: 10.1080/07900627.2014.924395

The three-geographical scales of transboundary river basins are illustrated in Figure 4-1. The three scales are: (a) the upper scale, referred to the portion of the basin within the territory of the upper riparian country; (b) basin-wide scale, referred to the entire watershed; and (c) the lower scale, referred to the portion of the basin within the territory of the lower riparian country.

Differences in institutional capacity, unilateral-based water exploitation schemes of the transboundary water in the upper country, the absence of technical cooperation between the upper and lower riparian actors, the mismanagement of water resources and the current insecure and unstable conditions in the lower riparian state have made it a complex problem that is difficult to resolve under the current circumstances.

Figure 4-1 underlines how transboundary countries may react in different manners and have different arrangements to manage the shared water resources. Potential basin-wide drought episodes would give the upper state a pretext to continue its unilateral water withdrawal practices and build additional storage reservoirs within its territory.

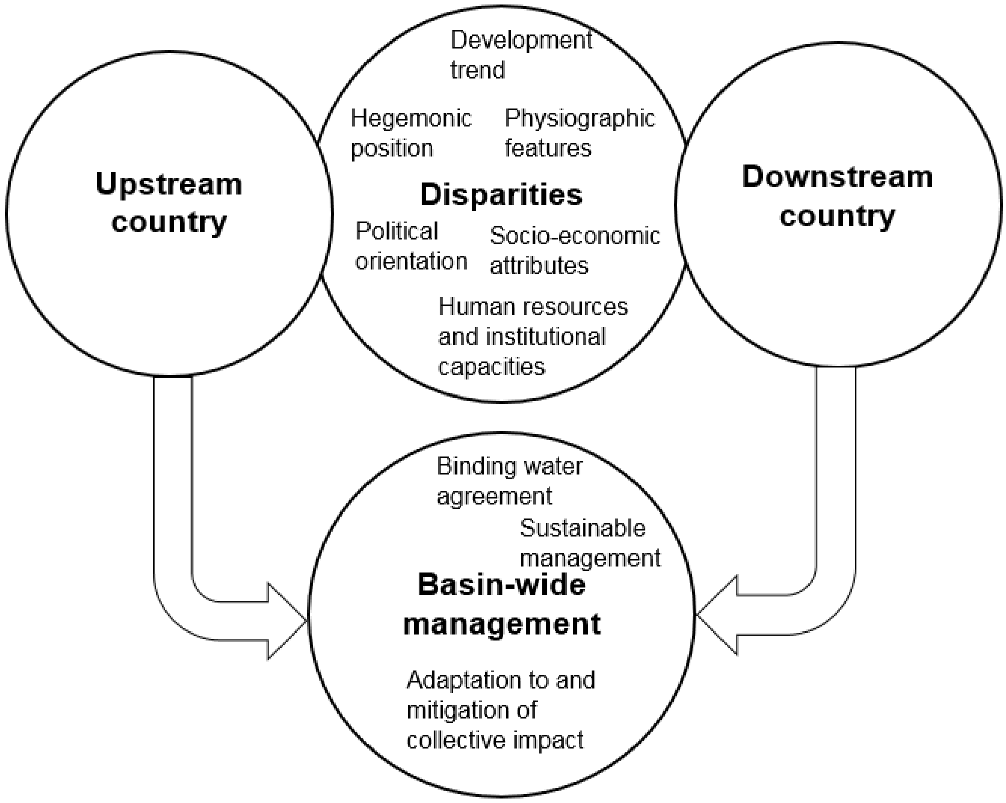

Figure 4-1: The three geographical scales and the disparities between riparian countries

The three-geographical scales highlighted that the collective impact of human-induced perturbations and successive drought spells would remarkably exacerbate the vulnerability of the downstream state to manage the water resources in a sustainable manner and to cope with the consequences of drought. The three-scalar presentation allows understanding of and an approach to the basin water management as a totality rather than depending on the country-based basin unit water governance policy. Moreover, it supports to profoundly understand the problem, thereby helping water managers to avoid biased plans and actions and lead to more informed decision-making in water management.

The disparities could open up an enabling environment in which adaptation to and mitigation of the combined impact of basin-wide climate change and human-induced interventions can be shaped. The three-geographical scales can be considered as a platform where vulnerability level can be assessed and appropriate actions to become more resilient can be taken. The platform offers better understanding of the problem and supports identification of thresholds for various variables. The three-scale demonstration of the problem is a first step in understanding how the transboundary river system could respond to increased collective impact of human pressure and basin-wide climate change, and its capacity to absorb changes.

4.2 Pre- and post-alteration flow regimes

The results and discussions presented in this section have been published in:

Al-Faraj, F. A. M., & Scholz, M. (2014). Assessment of temporal hydrologic anomalies coupled with drought impact for a transboundary river flow regime. The Diyala watershed case study. *Journal of Hydrology, 517*, 64-73.

4.2.1 Statistical summary of flow characteristics at natural condition

Table 4-1 summarizes statistical parameters of flow records calculated for different time frames at the examined gauging sites. The table encompasses the simple descriptive statistics for three unimpaired flow time series observed at the Derbandikhan hydrometric site, the Diyala discharge site and the side flow. The table is followed by three sub-sections that describe the detailed findings of the analysis of the pre- and post-anomalies flow regimes.

Table 4-1: Descriptive statistics of the unimpaired flow time series.

Statistical parameter		Derbandikhan hydrometric site (DHS) (1955-1982)		Diyala discharge site (DDS)		Side flow (1931-1961)
		Daily	Monthly	Daily (1931-1961)	Monthly (1925-1961)	Monthly
Mean (m^3/s)		173.1	173.5	173.4	169.4	44.9
Median (m^3/s)		108.0	112.6	87.0	97.1	32.5
Std. Deviation (m^3/s)		217.9	183.8	226.4	182.9	43.8
Coefficient of variation		1.26	1.06	1.08	1.08	0.97
Variance		47,502.7	33,798.4	51,276.5	33,479.7	1916.9
Range (m^3/s)		5815.0	1451.6	3328.0	1026.1	261.0
Minimum (m^3/s)		1.0	15.0	12.0	14.1	1.0
Maximum (m^3/s)		5816.0	1466.6	3340.0	1040.2	262.0
Percentiles (m^3/s)	25	68.0	74.1	42.0	45.1	9.0
	50	108.0	112.6	87.0	97.1	32.5
	75	203.0	215.8	215.0	229.4	68.8

4.2.1.1 Derbandikhan hydrometric site

The recorded daily discharges over the unaltered natural period (1955-1982) at the DHS vary between 1 m^3/s and 5816 m^3/s. The minimum flow was recorded on 1 October 1962, and the maximum flow was observed on 18 March 1974. The long-term mean daily flow rate is 173.10 m^3/s, accounting for about 5.46 billion m^3. The median and the standard deviation are 108 m^3/s and 217.95 m^3/s, respectively.

The coefficient of variation value of 1.26 is relatively high due to the high covariance between the extreme minimum and maximum values. The maximum value of 5816 m^3/s is approximately 34 times the long-term mean daily flow rate. The considerable flow variations during the unimpaired condition are predominantly attributed to the characteristic climatic periods (i.e. dry, normal and wet) of the hydrologic year. The rate of change in consecutive annual natural runoff depends mainly on the degree of annual precipitation anomaly with respect to the long-term mean annual precipitation.

Concerning the impaired condition, the hydrologic alteration can be attributed to annual climate conditions and the size of upstream human-induced river regulation schemes. The altered flow condition, the mean annual runoff and percentages relative to the long-term mean annual unaltered streamflow over the whole altered period (1983-2013) are shown in Table 4-2 and Figure 4-2. The relative yearly average discharges over the regulated period between 1983 and 1998 ranged from 0.57 in 1984 to 1.88 in 1988. In this period, two dams of 321 million m^3 storage capacity in total were inaugurated and 5968 ha of agricultural land and 810 ha of fish farms were served.

The last 15 years (1999-2013) indicated considerable recession where the relative mean annual flows ranged from 0.21 in 2008 to 0.79 in 2003. This period witnessed intensive regulation between 2004 and 2013, and two harsh drought periods (1999 to 2001, and 2008 to 2009). The relative mean annual runoff volumes dropped to very low levels during the drought time windows, where the relative mean annual flows ranged from 0.24 to 0.34 between 1999 and 2001, and from 0.21 to 0.24 between 2008 and 2009.

Table 4-2: Percentages of altered mean annual flow to long-term unaltered mean annual flow (Al-Faraj & Scholz, 2014a).

Year	Flow (m^3/s)	Flow volume (bcm)	% of long-term mean annual flow volume	Year	Flow (m^3/s)	Flow volume (bcm)	% of long-term mean annual flow volume
1983	180.46	5.69	1.04	1999	59.14	1.87	0.34
1984	98.34	3.10	0.57	2000	40.75	1.29	0.24
1985	245.30	7.74	1.42	2001	42.21	1.33	0.24
1986	136.79	4.31	0.79	2002	99.67	3.14	0.58
1987	179.82	5.67	1.04	2003	136.81	4.31	0.79
1988	311.37	9.82	1.80	2004	107.92	3.40	0.62
1989	150.06	4.73	0.87	2005	130.09	4.10	0.75
1990	147.53	4.65	0.85	2006	107.06	3.38	0.62
1991	119.21	3.76	0.69	2007	94.91	2.99	0.55
1992	261.47	8.25	1.51	2008	36.12	1.14	0.21
1993	141.74	4.47	0.82	2009	40.88	1.29	0.24
1994	203.69	6.42	1.18	2010	91.22	2.88	0.53
1995	222.06	7.00	1.28	2011	59.98	1.89	0.35
1996	141.48	4.46	0.82	2012	70.85	2.23	0.41
1997	104.88	3.31	0.61	2013	63.31	2.00	0.37
1998	221.51	6.99	1.28				
bcm: Billion m^3							

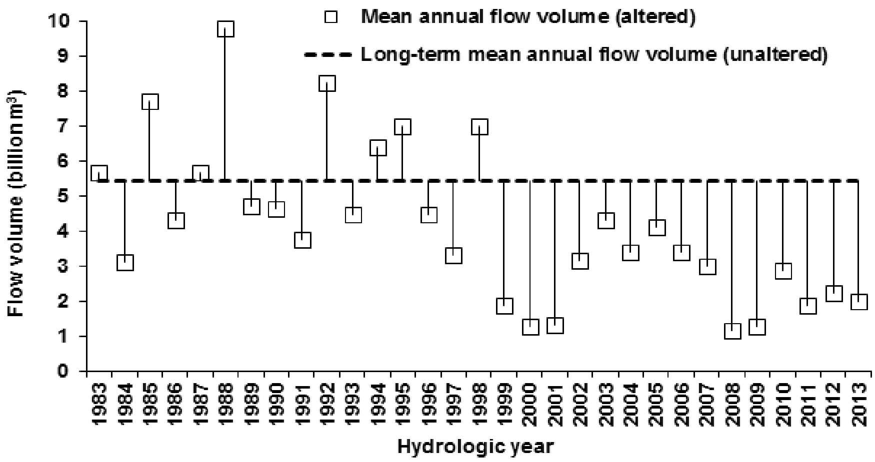

Figure 4-2: Annual deviation from the unaltered long-term mean annual flow volume (Al-Faraj & Scholz, 2014a).

The long-term median annual flow for the unaltered period (1955-1982) is estimated at 108 m^3/s. The median annual anomalies (%) of the whole altered timespan (1983-2013) were calculated using Equation 4.1 (UNEPA, 2011).

$$\text{Anomaly (\%)} = \frac{(AMF_{altered} - LTAMF_{unaltered})}{LTAMF_{unaltered}} \times 100 \qquad \text{Equation 4.1}$$

where AMFaltered and LTAMFunaltered (m^3/s) are the median annual flow in the post-regulation condition and long-term median annual flow for the whole pre-regulation condition, respectively. The anomalies of the median annual flow for the post-impact condition from the long-term unaltered median annual flow are shown in Table 4-3 and Figure 4-3. Findings reveal that the median annual flow values over the period 1983 to 1998 varied significantly between +100% in 1995 to −52.8% in 1997. A sharp shift in the natural flow regime has been observed over the last 15 years (1999-2013). The hydrologic anomalies ranged from −25.9% in 2003 to −81.9% in 2000. The median annual anomaly over the aforementioned period was estimated at −58.3%. These results indicate that the human-induced pressures in the upstream state, Iran, have left their negative impacts on the water availability for the downstream country, Iraq. Data evidence shows a considerable departure from the natural hydrologic variations occurring within the shared river basin.

The long-term median monthly flows of the pre-regulation period and the three altered time scales associated with their anomalies are illustrated in Table 4-4 and Figure 4-4. For the unaltered time window, the median flows ranged from 64.0 m^3/s in October to 325.3 m^3/s in April. In comparison, the median flows were between 26.5 m^3/s and 289.0 m^3/s, for the first altered time frame (1983-2013), between 16.0 m^3/s and 153.5 m^3/s for the second time slice (1999-2013), and between 16.5 m^3/s and 176.3 m^3/s, for the third time span (2004-2013) regarding post-regulation. The corresponding long-term median monthly flows ranged from +5.3% to −62.7%, −28.2% to −77.5%, and −23.6% to −76.8%. The maximum anomalies, which were observed in September, were −62.7%, −77.5% and −76.8%, respectively.

The non-rainy months (June-September) were associated with considerable anomalies. The anomalies over the two impacted periods 1999-2013 and 2004-2013 are considerably close to each other. The small differences could be attributed to both the influence of drought events that span the years 1999-2001 and 2008-2009, and the number of years examined in each time window. The considerable anomalies, particularly during the dry season, represent significant signatures of the anthropogenic pressures in the upper riparian country Iran, which reduces considerably the water available for the lower riparian state Iraq.

Table 4-3: Annual median anomaly between 1983 and 2013 (Al-Faraj & Scholz, 2014a).

Hydrologic year	Anomaly (%)	Hydrologic year	Anomaly (%)
1983	+25.0	1999	−67.6
1984	−33.3	2000	−81.9
1985	+92.6	2001	−76.9
1986	−10.2	2002	−50.9
1987	+16.7	2003	−25.9
1988	+66.7	2004	−35.2
1989	−9.3	2005	−48.1
1990	−3.7	2006	−58.3
1991	−38.9	2007	−55.6
1992	+39.4	2008	−77.8
1993	+14.8	2009	−76.9
1994	+54.6	2010	−43.5
1995	+100.0	2011	−64.8
1996	−42.1	2012	−70.4
1997	−52.8	2013	−55.6
1998	+2.8		

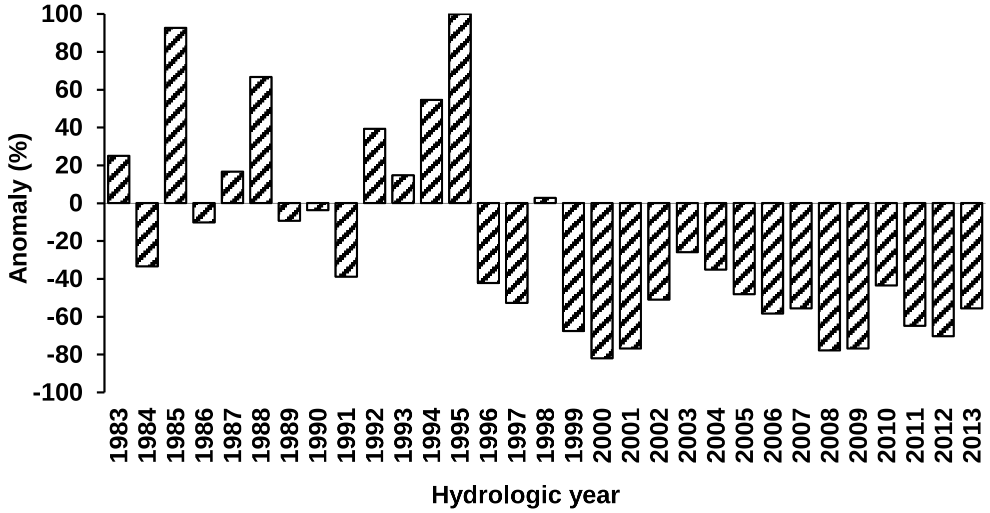

Figure 4-3: Annual median anomaly between 1983 and 2013 (Al-Faraj & Scholz, 2014a).

Table 4-4: Long-term monthly median flows and anomaly rates (Al-Faraj & Scholz, 2014a).

Month	Flow (m^3/s)					Anomaly (%)			
	1955-1982	1983-2003	1983-2013	1999-2013	2004-2013	1983-2003	1983-2013	1999-2013	2004-2013
October	64.0	58.0	33.0	19.0	21.5	-9.4	-48.4	-70.3	-66.4
November	72.3	67.0	55.0	32.5	36.0	-7.3	-23.9	-55.0	-50.2
December	89.0	117.0	61.0	35.0	39.5	31.5	-31.5	-60.7	-55.6
January	111.5	132.0	80.0	57.0	56.0	18.4	-28.3	-48.9	-49.8
February	170.5	183.0	179.5	122.5	130.3	7.3	5.3	-28.2	-23.6
March	298.5	329.0	220.0	128.0	175.0	10.2	-26.3	-57.1	-41.4
April	325.3	372.0	289.0	153.5	176.3	14.4	-11.2	-52.8	-45.8
May	190.0	190.0	155.0	115.0	115.5	0.0	-18.4	-39.5	-39.2
June	109.5	87.0	68.0	39.0	44.8	-20.5	-37.9	-64.4	-59.1
July	85.0	56.0	42.0	28.0	30.5	-34.1	-50.6	-67.1	-64.1
August	75.0	47.0	35.0	19.0	19.5	-37.3	-53.3	-74.7	-74.0
September	71.0	41.0	26.5	16.0	16.5	-42.3	-62.7	-77.5	-76.8

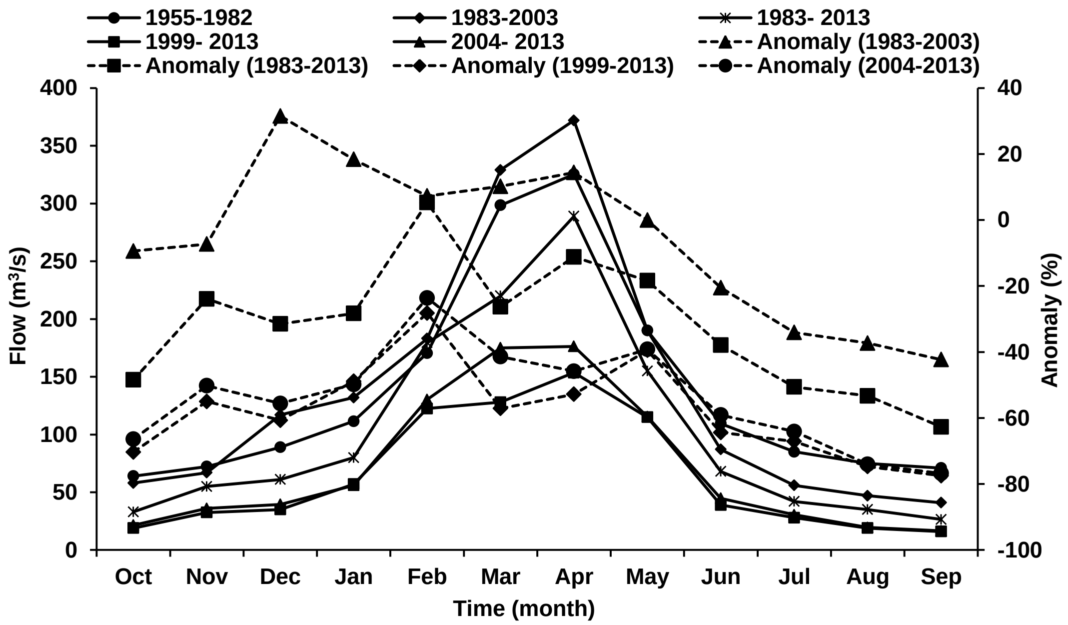

Figure 4-4: Long-term monthly median flows and rates of anomaly.

The magnitudes of extremes over several temporal scales (1-, 3-, 7-, 30- and 90-days) are calculated for both unaltered and altered time windows. Results are shown in Table 4-5, Figure 4-5 and Figure 4-6, indicating an overall statistically significant decrease in the 1-day to 90-days minima flows over the pre-1983 period. The rates of fall ranged from −33.3% to −53.8%. More considerable changes are observed for the period between 1999 and 2013 (particularly after 2004). The rates of anomaly ranged from −55.6% to −73.1% for the period between 1999 and 2013, and from −48.9% to −71.0% for the water years between 2004 and 2013. Concerning the 1-day to 90-days maxima flows, results illustrate that the rates of anomaly ranged from −9.0% to −24.6% over the whole period of alteration. Higher rates are observed over the hydrologic years 2004-2013. The rates of anomaly ranged from −44.8% to −49.8% for the time window between 1999 and 2013, and from −45.3% to −48.2% for the time frame between 2004 and 2013.

Table 4-5: Magnitude of annual extreme conditions (Al-Faraj & Scholz, 2014a).

Duration		Flow (m^3/s)				Anomaly (%)			
	1955-1982	1983-2003	1983-2013	1999-2013	2004-2013	1983-2003	1983-2013	1999-2013	2004-2013
1-day min	22.5	25.0	15.0	10.0	11.5	+11.1	−33.3	−55.6	−48.9
3-day min	34.3	29.0	17.7	11.7	12.7	−15.5	−48.5	−66.0	−63.1
7-day min	39.4	31.1	18.3	12.4	13.5	−21.1	−53.5	−68.4	−65.7
30-day min	53.4	35.9	24.7	14.4	15.5	−32.8	−53.8	−73.1	−71.0
90-day min	69.4	45.6	35.8	20.4	20.4	−34.3	−48.5	−70.7	−70.6
1-day max	912.0	1017.0	830.0	503.0	472.0	+11.5	−9.0	−44.8	−48.2
3-day max	803.7	812.1	606.3	403.3	423.2	+1.0	−24.6	−49.8	−47.3
7-day max	632.4	668.0	499.1	325.0	336.3	+5.6	−21.1	−48.6	−46.8
30-day max	463.2	489.6	409.8	241.2	253.6	+5.7	−11.5	−47.9	−45.3
90-day max	348.7	342.2	278.9	184.2	189.7	−1.9	−20.0	−47.2	−45.6

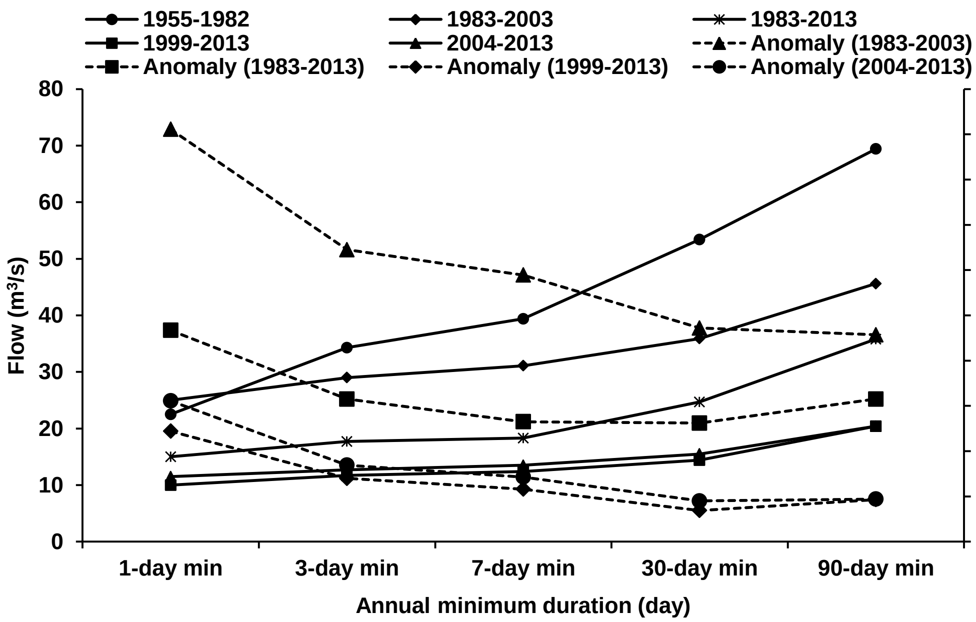

Figure 4-5: Magnitude of annual minima condition (*after* Al-Faraj & Scholz, 2014a).

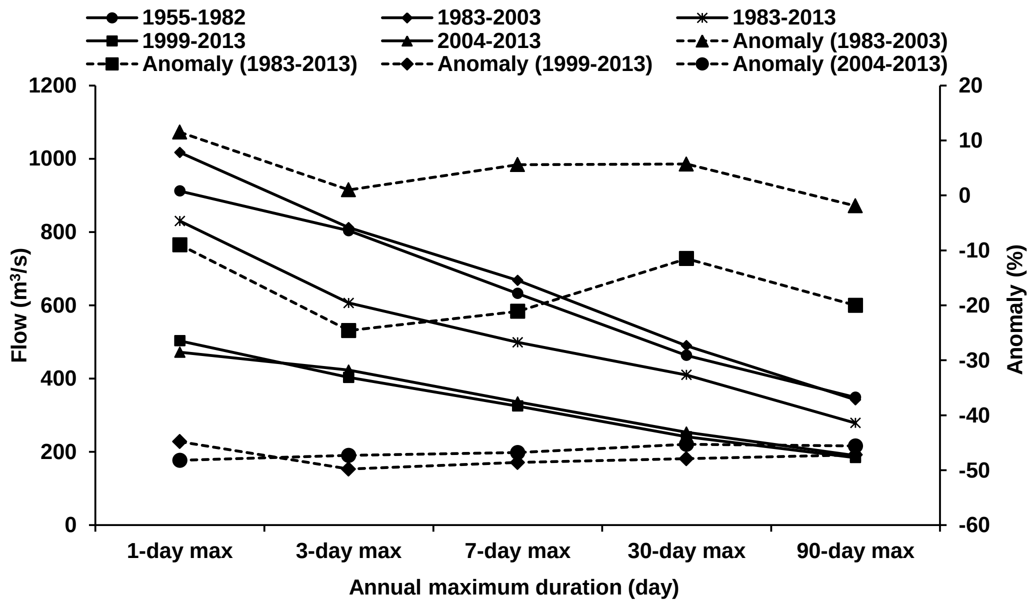

Figure 4-6: Magnitude of annual maxima condition (*after* Al-Faraj & Scholz, 2014a).

The FDC of daily flows observed at the DHS is shown in Figure 4-7. Percentiles are important statistical tools, which potentially indicate changes in a watershed's hydrologic characteristics. Some useful measures were extracted from the FDC: (a) Q20/Q90 = 5.83, (b) Q50/Q90 = 2.63, and (c) Q90/Q50 = 0.38, which indicates that the long-term ground water contribution to total runoff represents 38%. The magnitude of high flow centred at 5% (Q5) is equal to 505.2 m^3/s, accounting for about 15.93 billion m^3. Low flow centred at 95% (Q95) equals 24 m^3/s, about 0.76 billion m^3. Temporal percentiles (10th, 25th, 50th, 75th and 90th percentiles), which span the extreme flow thresholds for the unaltered and impaired periods are illustrated in Table 4-6 and Table 4-7. A close comparison between the results given in Table 4-6 and Table 4-7 indicates that the flow that was equal to or exceeded the threshold for 90% of the time for the non-rainy months (June-September) has declined on average by about 75%, 83%, and 77% for the three altered time slices, respectively.

The long-term annual reductions were about 55%, 64% and 60%, respectively. For the flow that was equal to or exceeded the threshold for 10% of the time for the non-rainy months (June-September), the drop is about 46%, 75% and 74%, respectively. The long-term annual reductions are about 19%, 49% and 55%, respectively. Considering the median flow, the flow that was equal to or exceeded the threshold for 50% of the time dropped by about 32%, 58% and 53%, respectively.

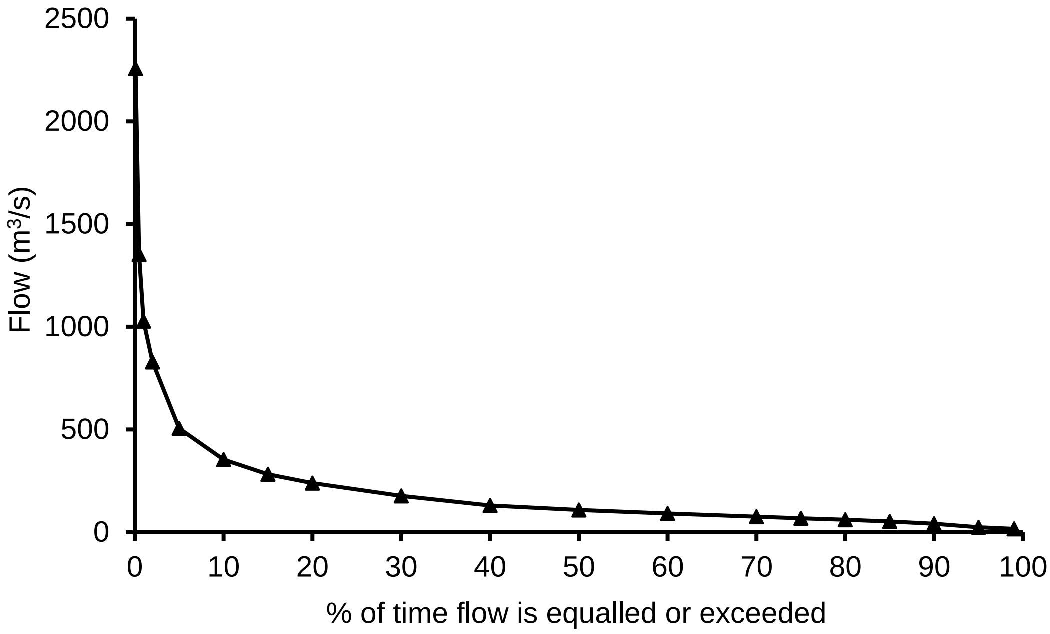

Figure 4-7: Flow duration curve of the unimpaired daily flow time series observed at the Derbandikhan hydrometric site (DHS).

Table 4-6: Percentiles for the unaltered flow condition 1955-1982 (Al-Faraj & Scholz, 2014a).

Month	Flow (m^3/s)				
	10%	25%	50%	75%	90%
October	17.9	36.5	64.0	93.8	114.0
November	31.4	56.9	72.3	105.8	129.5
December	51.3	63.8	89.0	112.8	139.6
January	62.9	79.5	111.5	149.3	216.1
February	86.7	130.9	170.5	242.5	282.8
March	137.2	206.5	298.5	395.5	547.0
April	186.4	245.6	325.3	463.5	845.4
May	121.5	146.0	190.0	292.3	692.6
June	48.8	73.6	109.5	172.3	215.1
July	30.2	52.5	85.0	106.8	179.0
August	24.2	42.0	75.0	101.8	131.0
September	18.7	33.3	71.0	87.9	117.6

Table 4-7: Temporal percentiles for the flow (m^3/s) of the four altered time windows (Al-Faraj & Scholz, 2014a).

Month	1983-2003					1983-2013					1999-2013					2004-2013				
	10%	25%	50%	75%	90%	10%	25%	50%	75%	90%	10%	25%	50%	75%	90%	10%	25%	50%	75%	90%
October	8.0	29.8	58.6	70.8	131.1	7.2	19.0	33.0	68.0	82.0	5.8	8.0	19.0	23.0	106.0	7.9	17.5	21.5	23.8	26.0
November	17.5	36.3	81.2	136.0	209.1	19.4	32.5	55.0	92.0	139.0	13.6	23.0	32.5	43.0	57.3	19.3	29.0	36.0	50.6	59.6
December	32.0	50.6	132.0	189.2	263.7	27.8	35.0	61.0	127.0	206.0	26.6	31.0	35.0	56.0	88.8	26.1	30.8	39.5	57.3	74.5
January	52.3	76.1	145.2	210.4	339.5	36.6	53.0	80.0	163.0	266.0	30.6	39.0	57.0	69.0	162.0	27.6	35.3	56.0	66.0	173.0
February	75.6	126.5	196.5	302.4	364.4	66.0	83.0	180.0	232.0	299.0	62.2	73.0	123.0	193.0	282.0	57.5	78.8	130.0	202.0	294.0
March	124.7	193.4	345.2	480.6	694.7	97.2	121.0	220.0	377.0	485.0	83.4	102.0	128.0	218.0	377.0	96.6	103.0	175.0	219.0	384.0
April	103.3	269.3	367.8	498.6	679.4	78.4	154.0	289.0	409.0	584.0	64.1	90.0	154.0	268.0	339.0	53.6	85.6	176.0	239.0	287.0
May	40.7	149.6	197.8	257.4	348.1	37.6	110.0	155.0	214.0	276.0	29.8	40.0	115.0	141.0	164.0	25.9	63.3	116.0	160.0	168.0
June	16.2	67.3	89.6	107.5	163.8	15.3	39.0	68.0	93.0	125.0	11.9	16.5	39.0	53.5	65.6	12.4	26.9	44.8	54.8	63.6
July	7.6	38.1	56.8	71.7	97.4	7.6	28.0	42.0	67.0	76.8	4.6	10.0	28.0	34.0	40.2	6.5	20.8	30.5	35.3	41.7
August	5.1	27.8	47.9	58.0	75.7	4.8	19.0	35.0	52.0	68.6	3.2	8.0	19.0	32.0	34.6	4.7	14.8	19.5	32.3	36.6
September	4.3	24.2	41.5	67.9	77.2	4.6	16.0	26.5	55.0	72.0	3.0	7.0	16.0	19.5	26.1	4.8	14.3	16.5	20.9	25.5

Validation of the hydrologic alteration. The validation focused mainly on the effect of damming and irrigation projects, which were put in place between 1983 and 2013 (Table 3-1 and Figure 3-3). Only one dam of 224 million m^3 storage capacity was inaugurated between 1983 and 1993. The agriculture and fish farm areas served by this dam are 3768 ha and 10 ha, respectively. The storage capacity accounts for 4.1% of the long-term mean annual unaltered flow volume and 12.7% of the total storage capacity of all dams in 2013. The mean annual flow volumes are higher than the long-term mean annual unaltered flow volume over a time period of only 5 out of 11 years. The ratios of yearly average runoff volumes are significantly ($p < 0.05$) high in 1985, 1988 and 1992. Substantial low ratios are observed in 1984 and 1991: 0.57 and 0.69, respectively (Table 4-2). The considerably high and low runoff ratios indicate that climate variability (dry, normal and wet years) has a considerable impact in addition to anthropogenic pressures in determining hydrologic alterations.

Between 1994 and 2003, another dam of 97 million m^3 storage capacity was commissioned to serve 2200 ha of irrigation area and 800 ha of fish farms. The storage capacity is about 5.9% of the long-term mean annual unaltered flow volume and 18.2% of the total storage capacity of all dams in 2013. The commissioning followed a period of drought events between 1999 and 2001, where the ratios of mean annual flow volumes ranged from 0.24 to 0.34. The mean annual runoffs were higher than the long-term yearly average unaltered flow volume over only 3 out of 10 years. The years 2004-2013 were characterized by very high levels of development. Seven dams with a storage capacity of 1463.6 million m^3 in total were inaugurated in addition to large-scale irrigation projects.

In 2013, the total storage capacity of all existing dams was 32.3% of the long-term mean annual unaltered flow volume and about 83% of the total storage capacity of all dams. Furthermore, dry years were recorded between 2008 and 2009. In 2018, the impact of artificial hydrologic alteration is likely to significantly increase when the Nosoud inter-basin water transfer tunnel and the Daryan dam will be in operation. The maximum annual flow volume that can be transferred via the Nosoud tunnel may be 2207.5 million m^3. The maximum amount of water that may be stored in reservoirs and diverted in 2018 could be about 4247 million m^3. Consequently, the annual flow volume that will be artificially harnessed and consumed in the upstream country will increase to about 78% of the long-term mean annual unaltered flow volume. This implies that only 22% of the long-term mean annual unimpaired flow volume is likely to be available to the downstream state in normal years. This ratio will be less in dry years.

General formulas. Three Generic empirical formulas have been proposed for estimating the altered mean annual flow volumes available to a downstream country. Equations 4.2 to 4.4 are of general application value to transboundary river basins in order to estimate the mean annual flow volume entering a downstream country from an upstream state.

$Q_c = C_1 \times Q_n$ Equation 4.2

$Q_{artificial} = C_2 \times Q_c$ Equation 4.3

$Q_{altered} = Q_c - Q_{artificial}$ Equation 4.4

where Q_c is the mean annual flow volume for altered climatic conditions; C_1 represents the ratio between the mean annual precipitation over the entire basin at the year under consideration and the long-term yearly average precipitation; Q_n is the mean annual flow volume at natural condition; $Q_{artificial}$ is the mean yearly flow volume for the altered anthropogenic condition; C_2 is the ratio of the total water consumption caused by anthropogenic disturbances to the long-term mean annual natural flow volume; and $Q_{altered}$ is the net mean annual flow volume available to the downstream country under both climate alteration and human-induced pressures. It is worth mentioning that C_1 and C_2 are annual variables. The ratio value C_1 depends on the climatic condition, and the proportion value C_2 depends on the annual water abstraction.

The three proposed empirical equations can be applied either on a small-scale using part of the basin (sub-basin) or for the entire basin. In this regard, a well-distributed and representative meteorological network is needed to accurately estimate the mean precipitation over the considered area. In addition, the availability of long-term flow series can be used as a cross-check for rainfall-runoff model calibration and validation tasks. The proposed equations can also be used to estimate the net altered annual flow volume for the ungauged river basins provided that reliable data are available with respect to precipitation and annual water withdrawals. Figure 4-8 shows the application of Equations 4.2 to 4.4 to estimate the climatic-induced flow and the altered flow over the period 1983-2010. It also shows how the equations 4.2 to 4.4 can be successfully used to differentiate between the climate-induced impact and upstream development.

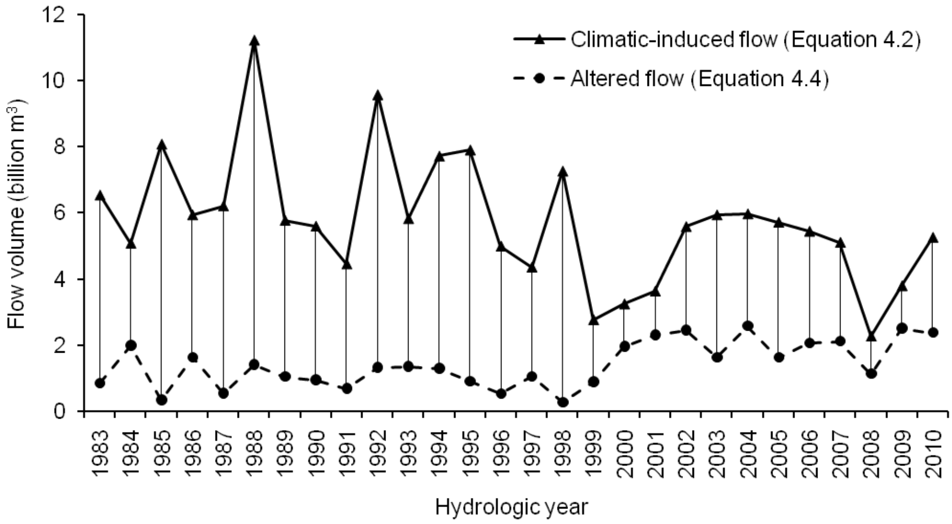

Figure 4-8: Climatic-induced flow and the altered flow using equations 4.2 to 4.4.

4.2.1.2 Diyala discharge site

The daily discharges observed at the DDS between 1931 and 1961 vary between 12 and 3340 m^3/s. The long-term mean daily flow equals 173.4 m^3/s, accounting for about 5.47 billion m^3. The high value of standard deviation of 226.4 m^3/s represents high variation or spread from the mean. The coefficient of variation equals 1.31. The flow duration analysis (Figure 4-9) reveals that at least 25% of discharges are less than or equal to 42 m^3/s or at least 75% are greater than or equal to 42 m^3/s. Similarly, for the 75th percentile, at least 75% of flow records are less than or equal to 215 m^3/s or at least 25% are greater than or equal to 215 m^3/s.

Interesting ratios relative to Q90 have been extracted from the flow duration analysis. These are: (a) Q20/Q90 = 9.74, (b) Q50/Q90 = 3.22, and (c) Q90/Q50 = 0.31, which implies that that the long-term signature of the groundwater to total runoff represents about 31%. High flow centred at 5% (Q5) is estimated at 584 m^3/s, about 18.42 billion m^3, while the low flow centred at 95% (Q95) is estimated at 22 m^3/s, about 0.69 billion m^3.

The monthly minimum, mean and maximum flows observed between 1925 and 1961 were 14.1 m^3/s, 169.53 m^3/s and 1040.2 m^3/s respectively.

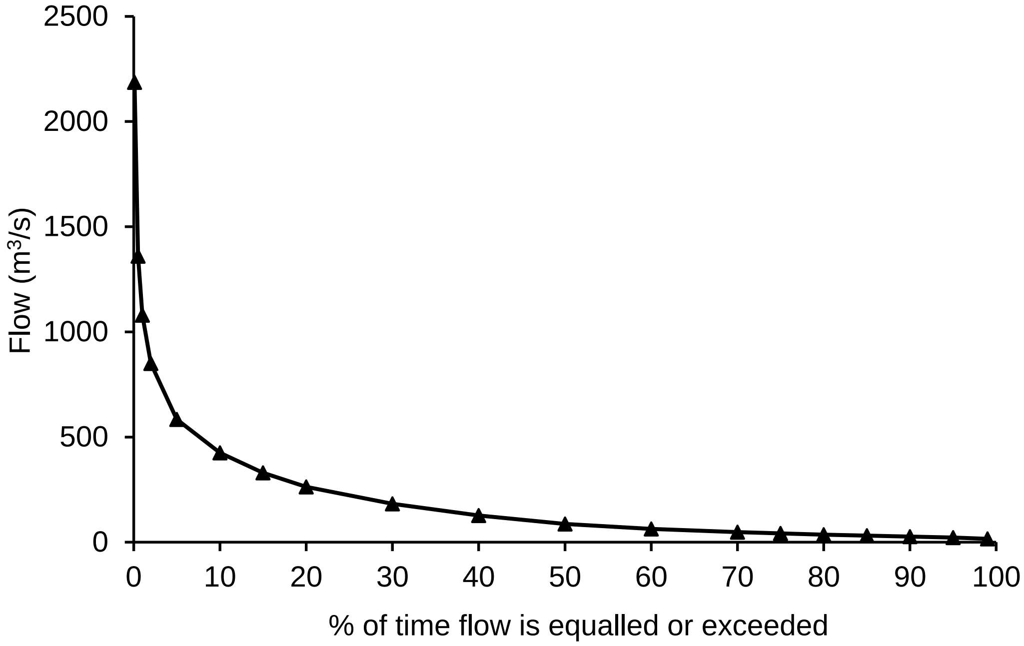

Figure 4-9: Flow duration curve of the daily flows observed at the Diyala discharge site (DDS) between 1931 and 1961.

4.2.1.3 Side flow between Derbandikhan hydrometric site and Diyala discharge site

The monthly discharges observed between 1931 and 1961 between the two discharge sites (DHS and DDS) vary between 1.00 and 262 m^3/s. The long-term mean monthly flow is estimated at about 45 m^3/s, accounting for approximately 1.42 billion m^3. The monthly flow duration analysis (Table 4-8) shows that at least 25% of the flow values are less than or equal to 9 m^3/s or at least 75% of the values are greater than or equal to 9 m^3/s. Similarly, for the 75th percentile, at least 75%

of the sorted values are less than or equal to 68.8 m^3/s or at least 25% of the values are greater than or equal to 68.8 m^3/s.

Table 4-8: Monthly flow duration analysis of the side flow between 1931 and 1961 (flow is given in m^3/s).

% of time flow is equalled or exceeded	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.1	262	150	222	237	112	68	36	24	15	28	87	110
0.5	262	150	222	237	112	68	36	24	15	28	87	110
1	262	150	222	237	112	68	36	24	15	28	87	110
2	262	150	222	237	112	68	36	24	15	28	87	110
5	218	140	212	200	109	66	32	19	13	24	77	94
10	105	118	190	156	100	62	29	12	8	16	47	67
15	90	114	136	142	94	53	27	11	8	12	39	60
20	83	108	129	130	88	49	23	10	7	9	35	54
25	78	94	120	121	78	45	18	9	6	9	33	48
30	67	92	115	119	75	42	14	7	5	8	25	47
40	61	81	99	105	71	35	10	6	4	7	20	45
50	55	78	89	90	69	32	8	5	3	5	17	37
60	51	69	81	77	63	27	8	4	3	4	16	29
70	46	65	73	67	56	21	5	3	2	3	14	24
75	42	64	67	66	48	19	5	3	2	3	13	22
80	35	60	64	61	43	17	4	2	2	3	12	20
85	31	58	61	59	41	17	4	2	2	2	12	20
90	28	51	53	56	40	15	3	2	2	2	9	17
95	19	25	39	45	30	13	3	2	1	1	6	15
99	18	25	28	42	22	12	3	2	1	1	1	14

Interesting ratios relative to Q90 have been extracted from the flow duration analysis. These are: (a) Q20/Q90 = 25.60, (b) Q50/Q90 = 10.83, and (c) Q90/Q50 = 0.092, which implies that that the long-term signature of the groundwater to total runoff represents about 9.2%. The minimum, mean and maximum annual flows over the water years 1931 and 1961 were 19.05 m^3/s (0.60 billion m^3), 44.76 m^3/s (1.41 billion m^3) and 71.68 m^3/s (2.26 billion m^3), respectively. The minimum was registered in 1960 while the maximum was recorded in 1954.

4.2.1.4 Relationship between the side flow and flow observed at Diyala discharge site

Figure 4-10 illustrates the annual runoffs of the side flow and the flow observed at the DDS between 1931 and 1961. A linear model, which represents the relationship between the monthly flows, is developed (Figure 4-11). The relationship is shown in Equation 4.5 with a correlation coefficient of 0.986.

$$Q_{SF} = 0.1921 Q_{DDS} + 10.173 \quad \text{Equation 4.5}$$

where Q_{SF} is the monthly side flow (m^3/s) and Q_{DDS} is the monthly flow observed at the DDS (m^3/s).

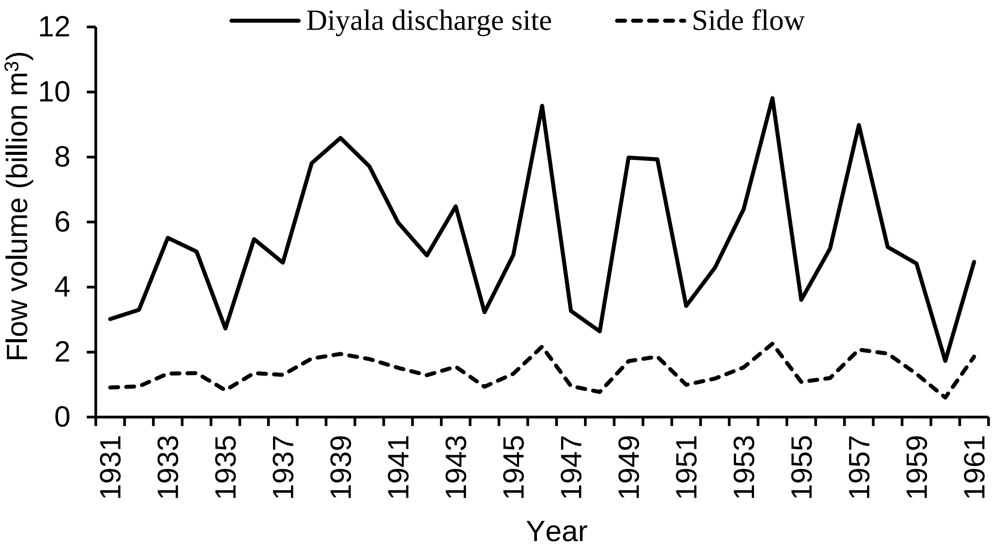

Figure 4-10: Annual runoff of the side flow and the flow observed at the Diyala discharge site (DDS) between 1931 and 1961.

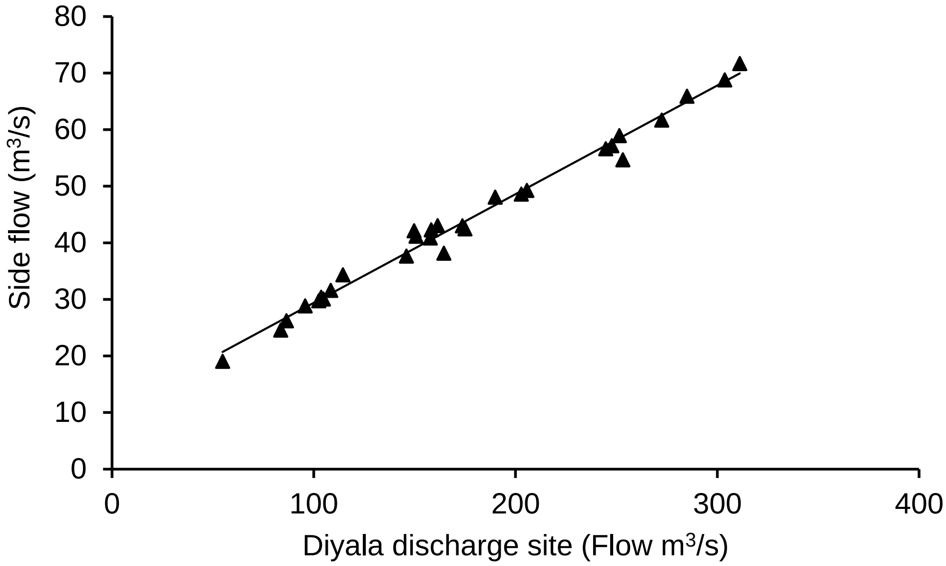

Figure 4-11: Relationship between the monthly side flow (SF) and the flow observed at the Diyala discharge site (DDS) between 1931 and 1961.

The annual relative contributions of the side flow (%) vary between about 21.6% in 1949 and approximately 40% in 1961 with a long-term average of nearly 27%. This implies that 40% of the area (11,900 km^2 out of 29,700 km^2) is producing 27% of the total runoff observed at the DDS.

The monthly time series observed at the DHS was extended back to start in 1931 instead of 1955 in order to produce a longer unimpaired time series. This was conducted through the combined use of Equation 4.5 and the developed linear model between observed and computed monthly flows between 1955 and 1961 at the DHS and DDS. The linear relationship (Figure 4-12) is given in Equation 4.6 with a correlation coefficient of 0.996 and a standard error of estimate of 14.77.

$$Q_{DHS(cal)} = 0.973Q_{DDS(obs)} - 4.4612 \qquad \text{Equation 4.6}$$

where $Q_{DHS(cal)}$ and $Q_{DDS(obs)}$ are the monthly calculated and observed flows at the DHS, respectively.

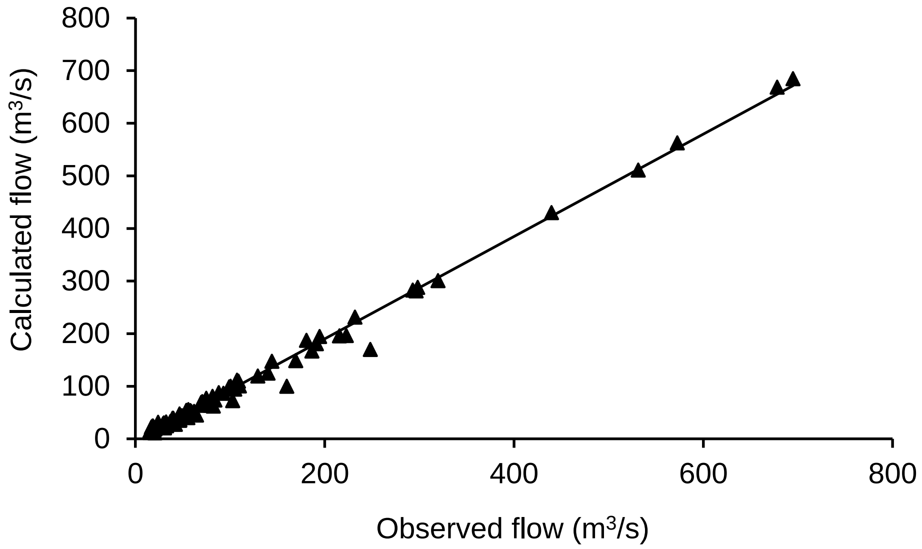

Figure 4-12: Relationship between observed and computed flows at the Derbandikhan hydrometric site (DHS) between 1955 and 1961.

The robust correlation between the observed and calculated monthly stream flows for a period of seven years (1955-1961) suggests that the observed and extended monthly streamflow time series at the DHS can be merged and used as one prolonged time series. It follows that 89 years of monthly flow records at the DHS covering the water years between 1925 and 2013, and 37 years spanning the hydrologic years between 1925 and 1961 at the DDS are generated for subsequent drought analysis, which eventually results in a series of drought states.

4.3 Meteorological data and drought indices characteristics

4.3.1 Meteorological data

The application of the double-mass curve analysis revealed no changes in instrumentation, observation procedures, gauge locations and other boundary conditions. This implies that the precipitation data of the 12 assessed meteorological stations are consistent and homogeneous. The descriptive statistics of the precipitation, mean air temperature and PET are shown in Table 4-9. A close examination of the table shows that the annual long-term minimum, maximum and mean temperatures of the Diyala basin for the period 1981 to 2010 are 11.2°C, 22.9°C and 16.8°C, respectively. The annual long-term minimum, maximum and mean PET are 1107.2 mm, 1629.9 mm and 1367.4 mm in that order. The annual long-term minimum, maximum and mean precipitations are 109.7 mm, 963.4 mm and 502.4 mm, respectively.

The ratios expressed as percentages of the long-term mean monthly precipitation to the long-term mean annual precipitations for the water years 1981 to 2010 are summarized in Table 4-10. Results reveal that the aggregated precipitation over the wet months (October to May) contributes as much as 99% of the total annual precipitation. Accumulated rainfall over the dry season (June to September) accounts for only 1% of the annual total. The proportion of precipitation between November and April represents approximately 90%. The ratios of precipitation in October and May together account for nearly 5% of the annual total.

Temperature and PET rate rises, and precipitation decreases are more pronounced over the time horizon 1998 to 2010 in comparison with the time period between 1981 and 1997 (Table 4-11). Findings regarding precipitation declines are confirmed by UNESCO (2014). Between 1998 and 2012, the reduction in total annual hydroelectric production in the Kurdish region of Iraq coincides with a fall in precipitation.

The proportions of increase in the rates of temperature and PET ranged from 4% to 14% and from 2% to 7%, respectively. The rates of reduction in precipitation fell between 16% and 31%. The average increase in temperature and PET rates over the entire basin were 8% and 4%, respectively. In contrast, the average drop in precipitation was 23%. The fractions of increase in PET rate exemplify about 48% to 60% of those detected in temperature, indicating an average of about 53%. The reduction in precipitation and increases in temperature and PET have widened the gap between precipitation and water demand, mainly for the agriculture sector.

Table 4-9: Descriptive statistics of the annual precipitation, temperature and potential evapotranspiration time series (Al-Faraj et al., 2014e).

ID	Station	Lat	Long	Altitude (masl)	P (mm)				T°C				PET (mm)			
					Min	Max	Mean	Stdev	Min	Max	Mean	Stdev	Min	Max	Mean	Stdev
IRN-1	Ghorveh	35.17	47.80	1906	165.7	569.7	383.5	103.7	8.5	13.4	11.2	1.1	931.1	1256.3	1107.2	69.7
IRN-2	Saghez	36.27	46.27	1523	148.5	736.0	461.8	157.1	7.9	15.5	11.5	1.8	897.8	1342.0	1126.1	101.5
IRN-3	Sanandaj	35.33	47.00	1373	170.0	720.0	435.5	134.3	11.1	15.5	13.7	1.0	1062.8	1336.5	1249.2	63.3
IRN-4	Ravansar	34.72	46.66	1363	197.9	888.4	572.3	162.4	12.5	16.3	14.8	0.9	1134.0	1364.1	1286.5	53.7
IRN-5	Eslamabad	34.13	46.43	1346	201.6	788.3	521.8	150.2	11.4	14.9	13.5	0.8	1097.3	1306.3	1240.6	51.3
IRN-6	Marivan	35.52	46.20	1287	446.4	1605.6	963.4	281.6	10.0	14.6	12.6	1.0	1034.7	1299.4	1182.8	60.5
IRN-7	Sarpolzahab	34.45	45.87	545	169.8	784.3	454.5	145.0	18.3	24.8	20.4	1.3	1444.9	1689.6	1525.6	51.3
IRQ-1	Dokan	35.95	44.95	499	240.5	1346.2	714.4	264.0	18.0	22.8	20.1	1.1	1440.5	1620.4	1518.6	38.9
IRQ-2	Derbandikhan	35.11	45.69	481	207.3	1083.8	623.4	225.9	18.8	23.1	20.9	1.1	1467.0	1632.1	1546.5	42.0
IRQ-3	Khanaqin	34.35	45.40	202	89.7	507.3	289.3	100.0	21.4	24.5	22.8	0.8	1571.8	1689.0	1628.0	31.2
IRQ-4	Baghdad	33.34	44.40	32	36.6	220.2	109.7	43.4	21.4	24.0	22.9	0.6	1574.8	1670.1	1629.9	23.1
IRQ-5	Sulaimaniya	35.55	45.43	824	230.1	1252.2	714.4	221.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 4-10: Ratios of long-term mean monthly to long-term mean annual precipitation (Al-Faraj et al., 2014e).

ID	Station	% of long-term annual precipitation											
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
IRN-1	Ghorveh	6.1	14.1	10.5	10.4	12.2	19.1	15.9	8.7	0.9	1.1	0.4	0.5
IRN-2	Saghez	6.2	13.7	12.0	12.3	13.7	15.9	15.0	8.3	1.1	1.0	0.5	0.3
IRN-3	Sanandaj	6.5	14.1	12.4	12.4	14.3	17.1	15.4	6.6	0.5	0.4	0.0	0.3
IRN-4	Ravansar	1.9	13.6	13.7	12.9	16.6	17.1	14.8	8.3	0.6	0.1	0.0	0.3
IRN-5	Eslamabad	4.6	15.5	14.6	16.5	16.2	17.3	10.8	3.6	0.2	0.2	0.0	0.3
IRN-6	Marivan	4.3	13.4	14.8	15.0	18.1	17.2	11.7	4.9	0.2	0.1	0.0	0.2
IRN-7	Sarpolzahab	2.6	12.9	16.0	17.8	15.2	18.7	11.5	5.2	0.1	0.1	0.0	0.1
IRQ-1	Dokan	4.6	12.0	16.7	17.7	18.4	16.6	10.3	3.1	0.2	0.1	0.1	0.2
IRQ-2	Derbandikhan	3.9	11.6	16.3	19.4	19.7	16.4	9.3	3.1	0.1	0.0	0.0	0.2
IRQ-3	Khanaqin	4.6	13.7	16.3	20.6	16.1	17.4	9.5	1.8	0.0	0.0	0.0	0.0
IRQ-4	Baghdad	3.4	14.5	15.7	21.9	13.3	16.2	12.1	2.8	0.1	0.0	0.0	0.0
IRQ-5	Sulaimaniya	4.9	12.5	15.2	17.1	17.5	15.2	11.9	5.4	0.2	0.0	0.0	0.2
Average		4.5	13.5	14.5	16.2	15.9	17.0	12.3	5.1	0.4	0.3	0.1	0.2

Table 4-11: Increase in temperature and potential evapotranspiration and reduction in precipitation. A comparison between two periods: (1981-1997) and (1998-2010) (Al-Faraj et al., 2014e).

ID	Station	Temperature	Potential evapotranspiration	Precipitation
		Increase (%)	Increase (%)	Reduction (%)
IRN-1	Ghorveh	13.00	7.00	22.25
IRN-2	Saghez	13.90	6.77	30.95
IRN-3	Sanandaj	10.70	5.29	26.66
IRN-4	Ravansar	6.24	3.50	20.30
IRN-5	Eslamabad	8.20	4.30	24.50
IRN-6	Marivan	10.00	5.00	20.14
IRN-7	Sarpolzahab	5.02	2.66	27.60
IRQ-1	Dokan	6.50	3.20	25.60
IRQ-2	Derbandikhan	8.30	4.00	16.00
IRQ-3	Khanaqin	3.60	2.14	25.50
IRQ-4	Baghdad	3.54	2.13	15.80
IRQ-5	Sulaimaniya	N/A	N/A	18.30

4.3.2 Mann-Kendall trend test for meteorological data and drought indices

Results from the M-K test of SPI for 3-, 6-, 9-, and 12-month time intervals (Table 4-12) indicate that the significant downward trend at a 5% level of significance has developed from 25% of the investigated meteorological stations for the 3-month time window to 75% for the 6-month time span aggregated precipitation and remained steady for 9- and 12-month time scales for cumulative precipitation. Marivan station in Iran and Sulaimaniya and Baghdad stations in Iraq presented no significant trend for the four overlapped periods. A comparison between the results of the M-K trend test of precipitation (Table 4-13) with the M-K trend test of SPI (Table 4-12), proved that there is a 100% match for three time intervals (6-, 9- and 12-month). Ghorveh station showed a mismatch for the 3-month time scale.

Correspondingly, the RDI (Table 4-14) findings designate that the M-K trend has grown from about 27% of the studied stations for the 3-month time interval to nearly 91% of the considered stations for the 6-month period. For 9- and 12-month time domains, the proportion was approximately 64% and 73%, respectively. Baghdad station in Iraq stands apart in that it demonstrated no significant trend for the four aggregated time frames. Marivan and Saghez stations in Iran displayed a significant trend for only the 6-month time scale. A comparison between the results of the M-K trend test of PET (Table 4-15) with the M-K trend test of RDI (Table 4-14), determines that there were differences for three time horizons (3-, 6- and 9-month). The corresponding proportions of PET and RDI were 36%, 45% and 82%, and 27%, 91%, and 64%, respectively. A 100% match was observed in the 12-month time domain. The differences could be attributed to the influence of precipitation in computing RDI.

The differences between the SPI and RDI M-K trend results could be attributed to (a) inaccessibility of mean air temperature data observed at Sulaimaniya station, meaning RDI was not obtained and consequently the number of stations for RDI computation was 11 instead of 12 for SPI, and (b) the influence of mean air temperature and correspondingly the PET on RDI development. Overall, findings suggest that the Diyala basin has been experiencing climatically induced changes. Climate change-induced alterations in temperature, PET and precipitation within the Diyala basin are likely to lead to a further reduction in annual flow volume entering the lower riparian country. The reduction in precipitation and the increase in temperature and PET rates have widened the gap between available water and water demand, particularly in the agriculture sector.

Table 4-12: The Mann-Kendall trend analysis of the standardized precipitation index (SPI) for four time intervals (Al-Faraj et al., 2014e).

ID	Name	3-month SPI			6-month SPI		
		M-K (tau)	P-value	Trend at 5%	M-K (tau)	P-value	Trend at 5%
IRN-1	Ghorveh	-0.237	0.069	insignificant	-0.411	0.001	significant
IRN-2	Saghez	-0.207	0.112	insignificant	-0.331	0.011	significant
IRN-3	Sanandaj	-0.186	0.155	insignificant	-0.37	0.004	significant
IRN-4	Ravansar	-0.182	0.166	insignificant	-0.297	0.022	significant
IRN-5	Eslamabad	-0.237	0.069	insignificant	-0.411	0.001	significant
IRN-6	Marivan	-0.205	0.117	insignificant	-0.223	0.087	insignificant
IRN-7	Sarpolzahab	-0.347	0.007	significant	-0.499	< 0.0001	highly significant
IRQ-1	Dokan	-0.269	0.038	significant	-0.292	0.024	significant
IRQ-2	Derbandikhan	-0.283	0.029	significant	-0.306	0.018	significant
IRQ-3	Khanaqin	-0.246	0.058	insignificant	-0.356	0.005	significant
IRQ-4	Baghdad	-0.186	0.155	insignificant	-0.207	0.112	insignificant
IRQ-5	Sulaimaniya	-0.177	0.177	insignificant	-0.154	0.242	Insignificant
ID	Name	9-month SPI			12-month SPI		
IRN-1	Ghorveh	-0.448	0.000	significant	-0.444	0.000	significant
IRN-2	Saghez	-0.375	0.003	significant	-0.375	0.003	significant
IRN-3	Sanandaj	-0.32	0.013	significant	-0.32	0.014	significant
IRN-4	Ravansar	-0.292	0.024	significant	-0.292	0.024	significant
IRN-5	Eslamabad	-0.448	0.000	significant	-0.444	0.000	significant
IRN-6	Marivan	-0.191	0.145	insignificant	-0.182	0.166	insignificant
IRN-7	Sarpolzahab	-0.393	0.002	significant	-0.393	0.002	significant
IRQ-1	Dokan	-0.255	0.049	significant	-0.264	0.041	significant
IRQ-2	Derbandikhan	-0.287	0.026	significant	-0.287	0.026	significant
IRQ-3	Khanaqin	-0.338	0.008	significant	-0.338	0.008	significant
IRQ-4	Baghdad	-0.145	0.272	insignificant	-0.145	0.272	insignificant
IRQ-5	Sulaimaniya	-0.131	0.321	insignificant	-0.131	0.321	insignificant

Table 4-13: The Mann-Kendall trend analysis of the precipitation (P) for four time intervals (Al-Faraj et al., 2014e).

ID	Name	3-month P			6-month P		
		M-K (tau)	P-value	Trend at 5%	M-K (tau)	P-value	Trend at 5%
IRN-1	Ghorveh	-0.262	0.044	significant	-0.425	0.001	significant
IRN-2	Saghez	-0.207	0.112	insignificant	-0.331	0.011	significant
IRN-3	Sanandaj	-0.186	0.155	insignificant	-0.370	0.004	significant
IRN-4	Ravansar	-0.182	0.166	insignificant	-0.297	0.022	significant
IRN-5	Eslamabad	-0.237	0.069	insignificant	-0.411	0.001	significant
IRN-6	Marivan	-0.205	0.117	insignificant	-0.223	0.087	insignificant
IRN-7	Sarpolzahab	-0.347	0.007	significant	-0.499	< 0.0001	highly significant
IRQ-1	Dokan	-0.269	0.038	significant	-0.292	0.024	significant
IRQ-2	Derbandikhan	-0.283	0.029	significant	-0.306	0.018	significant
IRQ-3	Khanaqin	-0.246	0.058	insignificant	-0.356	0.005	significant
IRQ-4	Baghdad	-0.184	0.159	insignificant	-0.205	0.117	insignificant
IRQ-5	Sulaimaniya	-0.177	0.177	insignificant	-0.154	0.242	insignificant
ID	Name	9-month P			12-month P		
IRN-1	Ghorveh	-0.366	0.004	significant	-0.343	0.008	significant
IRN-2	Saghez	-0.375	0.003	significant	-0.375	0.003	significant
IRN-3	Sanandaj	-0.320	0.013	significant	-0.320	0.013	significant
IRN-4	Ravansar	-0.292	0.024	significant	-0.292	0.024	significant
IRN-5	Eslamabad	-0.448	0.000	significant	-0.444	0.000	significant
IRN-6	Marivan	-0.191	0.145	insignificant	-0.182	0.166	insignificant
IRN-7	Sarpolzahab	-0.393	0.002	significant	-0.393	0.002	significant
IRQ-1	Dokan	-0.255	0.049	significant	-0.264	0.041	significant
IRQ-2	Derbandikhan	-0.287	0.026	significant	-0.287	0.026	significant
IRQ-3	Khanaqin	-0.338	0.008	significant	-0.338	0.008	significant
IRQ-4	Baghdad	-0.147	0.261	insignificant	-0.147	0.261	insignificant
IRQ-5	Sulaimaniya	-0.131	0.321	insignificant	-0.131	0.321	insignificant

Table 4-14: The Mann-Kendall trend analysis of the reconnaissance drought index (RDI) for four time intervals (Al-Faraj et al., 2014e).

ID	Name	3-month RDI			6-month RDI		
		M-K (tau)	P-value	Trend at 5%	M-K (tau)	P-value	Trend at 5%
IRN-1	Ghorveh	-0.203	0.120	insignificant	-0.503	< 0.0001	significant
IRN-2	Saghez	-0.195	0.135	insignificant	-0.320	0.013	significant
IRN-3	Sanandaj	-0.223	0.087	insignificant	-0.398	0.002	significant
IRN-4	Ravansar	-0.191	0.145	insignificant	-0.352	0.006	significant
IRN-5	Eslamabad	-0.246	0.058	insignificant	-0.398	0.002	significant
IRN-6	Marivan	-0.200	0.126	insignificant	-0.297	0.022	significant
IRN-7	Sarpolzahab	-0.375	0.003	significant	-0.503	< 0.0001	highly significant
IRQ-1	Dokan	-0.292	0.024	significant	-0.329	0.011	significant
IRQ-2	Derbandikhan	-0.306	0.018	significant	-0.333	0.009	significant
IRQ-3	Khanaqin	-0.237	0.069	insignificant	-0.366	0.004	significant
IRQ-4	Baghdad	-0.182	0.166	insignificant	-0.223	0.087	insignificant
IRQ-5	Sulaimaniya	N/A	N/A	N/A	N/A	N/A	N/A
ID	Name	9-month RDI			12-month RDI		
IRN-1	Ghorveh	-0.389	0.002	significant	-0.490	< 0.0001	significant
IRN-2	Saghez	-0.343	0.008	insignificant	-0.338	0.008	insignificant
IRN-3	Sanandaj	-0.407	0.001	significant	-0.398	0.002	significant
IRN-4	Ravansar	-0.356	0.005	significant	-0.343	0.008	significant
IRN-5	Eslamabad	-0.471	0.000	significant	-0.490	< 0.0001	highly significant
IRN-6	Marivan	-0.241	0.063	insignificant	-0.223	0.087	insignificant
IRN-7	Sarpolzahab	-0.393	0.002	significant	-0.398	0.002	significant
IRQ-1	Dokan	-0.292	0.024	significant	-0.278	0.032	significant
IRQ-2	Derbandikhan	-0.310	0.016	significant	-0.292	0.024	significant
IRQ-3	Khanaqin	-0.352	0.006	insignificant	-0.361	0.005	significant
IRQ-4	Baghdad	-0.177	0.177	insignificant	-0.172	0.189	insignificant
IRQ-5	Sulaimaniya	N/A	N/A	N/A	N/A	N/A	N/A

Table 4-15: The Mann-Kendall trend analysis of the potential evapotranspiration (PET) for four time intervals (Al-Faraj et al., 2014e).

ID	Name	3-month PET			6-month PET		
		M-K (tau)	P-value	Trend at 5%	M-K (tau)	P-value	Trend at 5%
IRN-1	Ghorveh	0.246	0.058	insignificant	0.361	0.005	significant
IRN-2	Saghez	0.108	0.416	insignificant	0.168	0.201	insignificant
IRN-3	Sanandaj	0.310	0.016	significant	0.297	0.022	significant
IRN-4	Ravansar	0.209	0.109	insignificant	0.228	0.081	insignificant
IRN-5	Eslamabad	0.260	0.045	significant	0.301	0.020	significant
IRN-6	Marivan	0.237	0.069	insignificant	0.246	0.058	insignificant
IRN-7	Sarpolzahab	0.172	0.189	insignificant	0.094	0.479	insignificant
IRQ-1	Dokan	0.255	0.049	significant	0.237	0.069	insignificant
IRQ-2	Derbandikhan	0.315	0.014	significant	0.375	0.003	significant
IRQ-3	Khanaqin	0.110	0.402	insignificant	0.209	0.109	insignificant
IRQ-4	Baghdad	0.200	0.126	insignificant	0.347	0.007	significant
IRQ-5	Sulaimaniya	N/A	N/A	N/A	N/A	N/A	N/A
ID	Name	9-month PET			12-month PET		
IRN-1	Ghorveh	0.425	0.001	significant	0.434	0.001	significant
IRN-2	Saghez	0.195	0.135	insignificant	0.205	0.117	insignificant
IRN-3	Sanandaj	0.407	0.001	significant	0.416	0.001	significant
IRN-4	Ravansar	0.264	0.041	significant	0.251	0.054	insignificant
IRN-5	Eslamabad	0.389	0.002	significant	0.421	0.001	significant
IRN-6	Marivan	0.274	0.035	significant	0.301	0.020	significant
IRN-7	Sarpolzahab	0.080	0.548	insignificant	0.117	0.376	insignificant
IRQ-1	Dokan	0.361	0.005	significant	0.444	0.000	significant
IRQ-2	Derbandikhan	0.476	0.000	significant	0.462	0.000	significant
IRQ-3	Khanaqin	0.338	0.008	significant	0.320	0.013	significant
IRQ-4	Baghdad	0.499	<0.0001	significant	0.531	<0.0001	highly significant
IRQ-5	Sulaimaniya	N/A	N/A	N/A	N/A	N/A	N/A

Comparability analyses were performed to assess differences between the SPI and the RDI_{st}. Results show that both indices often have comparable trends and respond in a similar manner. Robust coefficients of determination (r^2) were obtained between both indices for the four reference time intervals (3 to 12 months) regarding all investigated meteorological stations. The r^2 ranged from 0.71 to 0.99 (Table 4-16).

The corresponding means were 0.984, 0.901, 0.967 and 0.984 for 3, 6, 9 and 12 months, respectively. This suggests that both the SPI and RDI respond in a similar manner, and thus can be applied effectively to explore and analyse droughts for various time intervals. However, it is important to mention that the lower values of r^2 are observed for the 6-month interval, in which the low temperature of the winter months has an important role. Therefore, the RDI seems to depict in more detail the drought conditions, especially in winter months, due to the utilization of the PET.

Table 4-16: Coefficient of determination between the SPI and the RDIst.

ID	Station	Coefficient of Determination (r^2)			
		3-months	6-months	9-months	12-months
IRN-1	Ghorveh	0.9393	0.7096	0.9108	0.9582
IRN-2	Saghez	0.9642	0.7845	0.9265	0.9609
IRN-3	Sanandaj	0.9751	0.8459	0.9537	0.9780
IRN-4	Ravansar	0.9986	0.8801	0.9591	0.9822
IRN-5	Eslamabad	0.9973	0.9015	0.9679	0.9898
IRN-6	Marivan	0.9648	0.8287	0.9457	0.9762
IRN-7	Sarpolzahab	0.9940	0.9828	0.9895	0.9916
IRQ-1	Dokan	0.9972	0.9903	0.9945	0.9968
IRQ-2	Derbandikhan	0.9983	0.9915	0.9950	0.9965
IRQ-3	Khanaqin	0.9977	0.9962	0.9973	0.9980
IRQ-4	Baghdad	0.9993	0.9984	0.9992	0.9994

The annual initial values of the RDI (α_{12}), which is the ratio of annual precipitation to the annual PET, were calculated using Equation 2.10 (Table 4-17). The deviation from the long-term mean annual initial value of the RDI ($\overline{\alpha}_{12}$) ($\alpha_{12} - \overline{\alpha}_{12}$) (Table 4-18) gives a signature of drought, while the deviation from the threshold (0.7×$\overline{\alpha}_{12}$) provides a sign of severe drought (Tsakiris & Vangelis, 2005). This threshold is often empirically considered as the value below which drought is severe. A close screening of the results shown in Table 4-17 and Table 4-18 suggests that the most severe drought spells took place during the water years 1999 to 2001 and the hydrologic years 2008 and 2009. This complies with what was reported by UNESCO (2014). During the drought between 2007 and 2009, cropland throughout Iraq experienced reduced coverage, and livestock was decimated. The situation in 2009 caused a significant number of rural inhabitants to relocate in search of more sustainable access to drinking water and livelihoods.

Some sporadic severe episodes of drought were noted at some stations such as Sanandaj, Ravansar and Eslamabad in 1991, and Derbandikhan in 1996 and 1997. Moreover, Saghez, Eslamabad, Marivan, Dokan, Derbandikhan, Khanaqin and Baghdad encountered severe droughts in 2009.

Findings show that the basin has suffered from the most significant drought events in 1999, 2000 and 2008. Results suggest that in 2008 both the annual SPI and RDI indices indicated that nearly the entire basin was under am extreme drought condition, while a small proportion experienced moderate drought patterns. In 2000, the annual SPI and RDI reported similar drought tendencies, where the upper and lower parts of the basin suffered from moderate droughts, while the remaining areas witnessed extreme drought conditions. For SPI, the year 1999 had impressively similar drought patterns to the year 2000. Although similar drought patterns between the SPI and RDI were observed for the lower segment of the basin, dissimilarity was observed for the middle and upper areas.

Table 4-17: Annual initial values of the Reconnaissance Drought Index (RDI). (Table 4-17 continues on next page.)

Water year	Initial value of RDI (α_{12})										
	Ghorveh	Saghez	Sanandaj	Ravansar	Eslamabad	Marivan	Sarpolzahab	Dokan	Derbandikhan	Khanaqin	Baghdad
1981	0.450	0.463	0.470	0.659	0.607	0.928	0.418	0.568	0.637	0.253	0.088
1982	0.500	0.474	0.520	0.490	0.666	0.950	0.368	0.575	0.557	0.232	0.095
1983	0.490	0.690	0.530	0.521	0.605	0.942	0.325	0.517	0.501	0.192	0.047
1984	0.450	0.346	0.430	0.450	0.518	0.625	0.258	0.243	0.327	0.146	0.052
1985	0.520	0.517	0.470	0.696	0.597	1.043	0.508	0.615	0.636	0.315	0.068
1986	0.410	0.386	0.410	0.508	0.477	0.732	0.329	0.454	0.443	0.184	0.104
1987	0.350	0.396	0.320	0.506	0.426	0.734	0.286	0.474	0.429	0.161	0.029
1988	0.480	0.637	0.510	0.625	0.488	1.260	0.465	0.900	0.713	0.255	0.095
1989	0.310	0.301	0.330	0.374	0.417	0.665	0.262	0.369	0.425	0.105	0.085
1990	0.340	0.391	0.300	0.456	0.435	0.765	0.422	0.474	0.444	0.200	0.087
1991	0.270	0.333	0.220	0.298	0.293	0.766	0.276	0.451	0.301	0.169	0.061
1992	0.390	0.780	0.410	0.608	0.591	1.486	0.412	0.727	0.426	0.217	0.045
1993	0.330	0.564	0.320	0.432	0.435	0.861	0.288	0.635	0.436	0.191	0.138
1994	0.390	0.633	0.460	0.446	0.411	1.004	0.319	0.590	0.355	0.181	0.055
1995	0.500	0.625	0.560	0.615	0.586	1.239	0.396	0.741	0.342	0.283	0.096
1996	0.310	0.413	0.300	0.438	0.339	0.817	0.259	0.435	0.265	0.185	0.073
1997	0.250	0.419	0.320	0.314	0.296	0.745	0.229	0.345	0.253	0.154	0.023
1998	0.430	0.538	0.440	0.616	0.537	1.046	0.407	0.693	0.494	0.271	0.106
1999	0.180	0.198	0.140	0.237	0.245	0.347	0.170	0.194	0.154	0.103	0.033

Water year	Initial value of RDI (α_{12})										
	Ghorveh	Saghez	Sanandaj	Ravansar	Eslamabad	Marivan	Sarpolzahab	Dokan	Derbandikhan	Khanaqin	Baghdad
2000	0.230	0.281	0.220	0.246	0.192	0.549	0.130	0.235	0.178	0.062	0.038
2001	0.240	0.263	0.200	0.292	0.282	0.430	0.285	0.293	0.193	0.215	0.065
2002	0.260	0.398	0.280	0.358	0.371	0.873	0.290	0.460	0.561	0.210	0.051
2003	0.270	0.512	0.290	0.422	0.320	1.033	0.262	0.520	0.519	0.128	0.052
2004	0.260	0.406	0.330	0.478	0.403	0.872	0.309	0.575	0.440	0.160	0.084
2005	0.310	0.426	0.300	0.456	0.480	0.827	0.279	0.512	0.465	0.184	0.049
2006	0.290	0.360	0.290	0.453	0.463	0.747	0.230	0.436	0.410	0.118	0.085
2007	0.460	0.343	0.440	0.418	0.395	0.740	0.111	0.395	0.370	0.157	0.076
2008	0.140	0.117	0.130	0.155	0.162	0.387	0.169	0.160	0.132	0.054	0.037
2009	0.310	0.195	0.260	0.338	0.274	0.491	0.327	0.197	0.209	0.117	0.047
2010	0.340	0.153	0.340	0.497	0.398	0.708	0.174	0.370	0.523	0.142	0.058
Long-term mean	0.349	0.419	0.351	0.447	0.424	0.820	0.299	0.472	0.405	0.178	0.067
Threshold	0.244	0.293	0.246	0.313	0.297	0.574	0.209	0.330	0.283	0.125	0.047

Table 4-18: Deviation from the long-term mean annual initial value of the Reconnaissance Drought Index (RDI). (Table 4-18 continues on next page.)

Water year	$\alpha_{12} - \overline{\alpha}_{12}$										
	Ghorveh	Saghez	Sanandaj	Ravansar	Eslamabad	Marivan	Sarpolzahab	Dokan	Derbandikhan	Khanaqin	Baghdad
1981	0.101	0.044	0.119	0.212	0.183	0.108	0.119	0.097	0.233	0.075	0.020
1982	0.151	0.055	0.169	0.043	0.243	0.130	0.069	0.103	0.152	0.054	0.027
1983	0.141	0.271	0.179	0.074	0.181	0.121	0.026	0.045	0.096	0.014	**-0.020**
1984	0.101	**-0.072**	0.079	0.004	0.094	**-0.195**	**-0.041**	**-0.229**	**-0.078**	**-0.033**	**-0.016**
1985	0.171	0.099	0.119	0.249	0.173	0.222	0.210	0.143	0.231	0.137	0.001
1986	0.061	**-0.033**	0.059	0.062	0.054	**-0.088**	0.030	**-0.018**	0.038	0.005	0.037
1987	0.001	**-0.023**	**-0.031**	0.060	0.002	**-0.086**	**-0.013**	0.002	0.025	**-0.017**	**-0.039**
1988	0.131	0.219	0.159	0.178	0.064	0.439	0.166	0.428	0.308	0.077	0.027
1989	**-0.039**	**-0.117**	**-0.021**	**-0.072**	**-0.007**	**-0.155**	**-0.037**	**-0.103**	0.021	**-0.073**	0.018
1990	**-0.009**	**-0.028**	**-0.051**	0.009	0.012	**-0.055**	0.124	0.002	0.040	0.022	0.020
1991	**-0.079**	**-0.085**	**-0.131**	**-0.149**	**-0.131**	**-0.054**	**-0.023**	**-0.021**	**-0.104**	**-0.009**	**-0.007**
1992	0.041	0.362	0.059	0.161	0.167	0.665	0.113	0.255	0.021	0.039	**-0.022**
1993	**-0.019**	0.145	**-0.031**	**-0.015**	0.011	0.040	**-0.011**	0.163	0.032	0.013	0.070
1994	0.041	0.214	0.109	**-0.001**	**-0.013**	0.183	0.021	0.118	**-0.050**	0.003	**-0.012**
1995	0.151	0.207	0.209	0.168	0.162	0.418	0.097	0.269	**-0.062**	0.105	0.029
1996	**-0.039**	**-0.006**	**-0.051**	**-0.009**	**-0.085**	**-0.003**	**-0.039**	**-0.037**	**-0.139**	0.007	0.005
1997	**-0.099**	0.000	**-0.031**	**-0.133**	**-0.128**	**-0.075**	**-0.070**	**-0.126**	**-0.152**	**-0.024**	**-0.045**
1998	0.081	0.120	0.089	0.170	0.113	0.226	0.108	0.222	0.089	0.093	0.038

Water year	$\alpha_{12} - \overline{\alpha}_{12}$										
	Ghorveh	Saghez	Sanandaj	Ravansar	Eslamabad	Marivan	Sarpolzahab	Dokan	Derbandikhan	Khanaqin	Baghdad
1999	**-0.169**	**-0.221**	**-0.211**	**-0.210**	**-0.178**	**-0.474**	**-0.129**	**-0.278**	**-0.251**	**-0.075**	**-0.034**
2000	**-0.119**	**-0.137**	**-0.131**	**-0.200**	**-0.231**	**-0.271**	**-0.169**	**-0.237**	**-0.226**	**-0.116**	**-0.030**
2001	**-0.109**	**-0.155**	**-0.151**	**-0.154**	**-0.141**	**-0.390**	**-0.014**	**-0.179**	**-0.212**	0.037	**-0.002**
2002	**-0.089**	**-0.021**	**-0.071**	**-0.089**	**-0.052**	0.052	**-0.009**	**-0.012**	0.157	0.032	**-0.016**
2003	**-0.079**	**0.093**	**-0.061**	**-0.024**	**-0.104**	0.212	**-0.037**	0.048	0.114	**-0.050**	**-0.016**
2004	**-0.089**	**-0.013**	**-0.021**	0.032	**-0.021**	0.051	0.010	0.103	0.035	**-0.018**	0.017
2005	**-0.039**	0.007	**-0.051**	0.009	0.056	0.007	**-0.020**	0.040	0.061	0.006	**-0.018**
2006	**-0.059**	**-0.059**	**-0.061**	0.006	0.040	**-0.073**	**-0.069**	**-0.036**	0.005	**-0.060**	0.018
2007	0.111	**-0.075**	0.089	**-0.028**	**-0.029**	**-0.081**	**-0.188**	**-0.077**	**-0.034**	**-0.021**	0.009
2008	**-0.209**	**-0.302**	**-0.221**	**-0.292**	**-0.262**	**-0.433**	**-0.129**	**-0.311**	**-0.272**	**-0.125**	**-0.030**
2009	**-0.039**	**-0.224**	**-0.091**	**-0.109**	**-0.150**	**-0.330**	0.028	**-0.274**	**-0.196**	**-0.061**	**-0.021**
2010	**-0.009**	**-0.266**	**-0.011**	0.050	**-0.025**	**-0.113**	**-0.124**	**-0.102**	0.118	**-0.036**	**-0.009**

4.4 Sensitivity of surface runoff

The results and discussions presented in this section have been published in the paper shown below:

Al-Faraj, F. A. M., Scholz, M., & Tigkas, D. (2014d). Sensitivity of surface runoff to drought and climate change: Application for shared river basins. *Water, 6*(10): 3033-3048.

Results indicate promising outcomes of the Medbasin-M rainfall-runoff model during the calibration and validation stages. The statistics r, RMSE, MAE and IoA are 0.893, 2.117, 1.733 and 0.852, respectively, during the calibration. After validation, the corresponding statistics are 0.762, 1.250, 1.093 and 0.863 in this order. This consolidates the valid use of the model for further analysis such as running the synthetic climatic scenarios and determining the proportional change (%) in the mean annual runoff relative to the normal climatic condition. The simulated runoff volumes for the calibrated and validated periods against the observed runoff data are illustrated in Figure 4-13.

Figure 4-14 illustrates the RDIst over a period of 30-years between 1962 and 1991. The period of eight years of nearly normal climatic conditions (1975 to 1982) was picked for running the climatic scenarios. This period experienced no extreme events, and the average value of RDIst is close to zero. Moreover, findings reveal that the reference mean annual runoff, the initial value of the RDI (α_{12}), the RDIst and the SDI are as much as 4.87 billion m^3, 0.55, 0.09 and 0.16, respectively.

For an extreme climatic condition with a 40% reduction in P and a 30% increase in PET, the anticipated mean annual runoff, the α_{12}, the RDIst and the SDI were about 0.84 billion m^3, 0.26, −3.26 and −3.71, respectively. The projected mean annual runoff for the worst case scenario represents about 17.3% of that referred to as the ‘0 scenario’ (4.87 billion m^3).

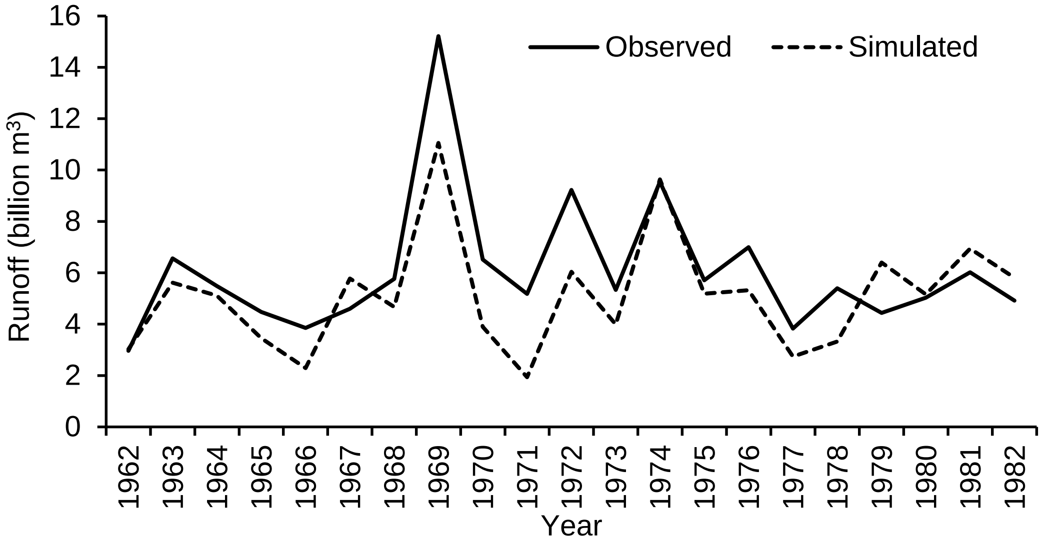

Figure 4-13: Simulated runoff data against the observed runoff records.

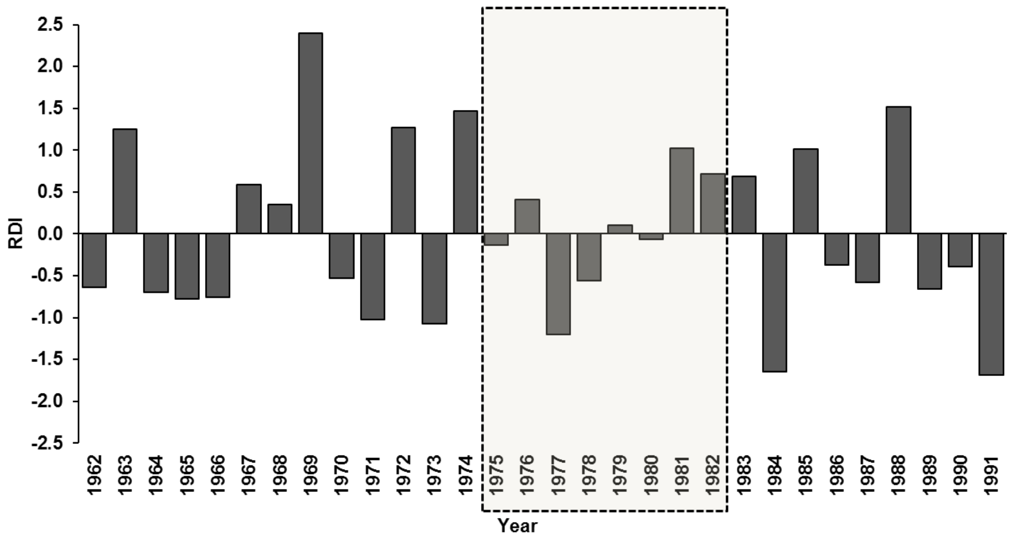

Figure 4-14: Selected simulation period for the Reconnaissance Drought Index (RDI) applied for different climatic scenarios concerning the Diyala example basin.

Findings suggest that a considerable impact could be caused by climate change on the availability of water resources, particularly for the lower riparian country.

Likewise, the results highlight the importance and the urgent need for pro-active plans and actions to cope with the most critical impact of drought and climate change. High-level coordination is required between all relevant parties to reduce the negative impacts, and moderate the economic and environmental losses. Furthermore, successful treatments need to be found to address the consequences that are likely to extend for a longer period after the end of the drought situation.

Figure 4-15 shows the foreseen change (%) in the annual runoff relative to the reference mean annual runoff value referred to as the '0 scenario'. It should be stressed that the 0 scenario is based on the climate conditions of 1975-1982, therefore the percentage of runoff change refers to that period. This figure provides a simple and useful tool that can be used by water managers and decision-makers to obtain the likely reduction (%) of the mean annual runoff according to a wide range of anomalies in P and PET.

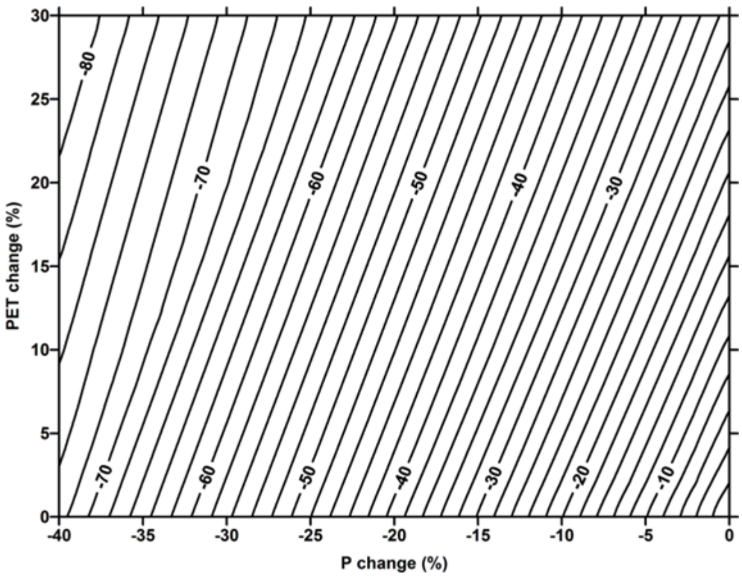

Figure 4-15: Foreseen runoff changes (%) of the upper Diyala example basin for an array of climatic changes for precipitation (P) and potential evapotranspiration (PET).

Figure 4-16 and Figure 4-17 demonstrate the anticipated RDIst and SDI values, respectively, according to possible changes in climatic condition (P and PET). For water governance decision-making, the problem becomes far more complex, because it deals not only with average anomalies, but also, and more decisively, with extreme events like severe prolonged drought spells.

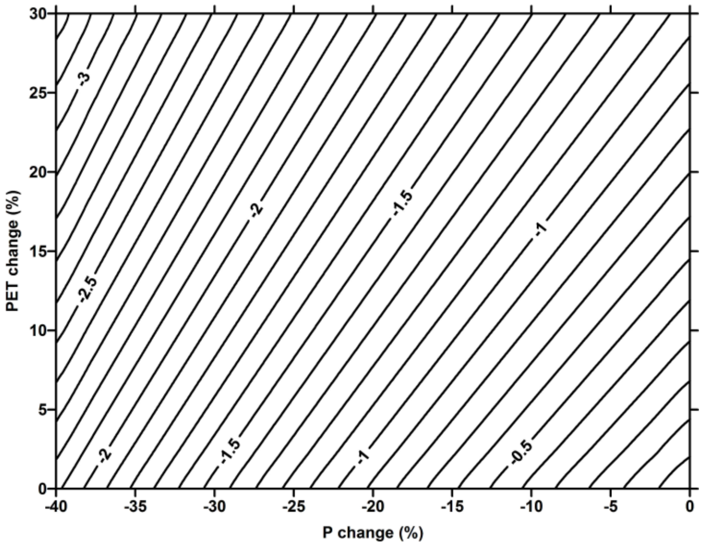

Figure 4-16: Anticipated standardized Reconnaissance Drought Index (RDIst) for the upper Diyala example basin regarding a wide range of climatic scenarios for precipitation (P) and potential evapotranspiration (PET).

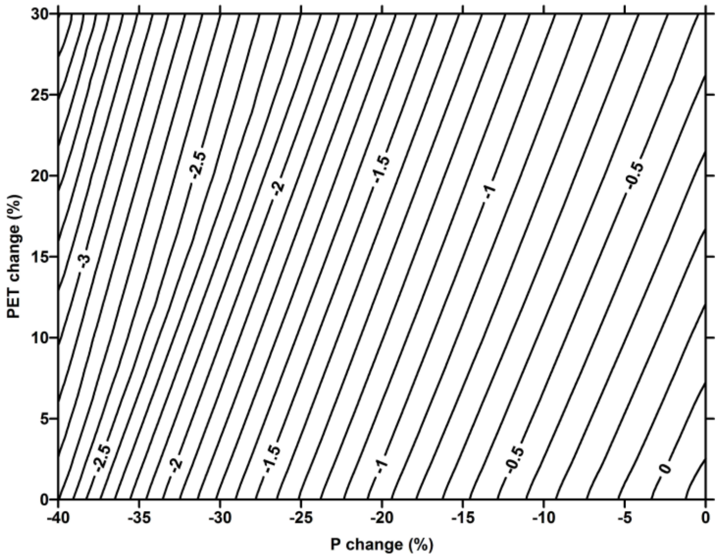

Figure 4-17: Anticipated Streamflow Drought Index (SDI) for the upper Diyala example basin regarding a wide range of climatic scenarios for precipitation (P) and potential evapotranspiration (PET).

Results reveal a robust relationship between the predicted RDIst and SDI values for all examined scenarios (Figure 4-18). Moreover, both RDIst and SDI vary according to drought severity in a similar manner. It is noteworthy to highlight that Figure 4-15 to

Figure 4-17 collectively represent a solid measure for drought and climate change signatures. The associated methodology should be part of a simple and generic tool that can be used by water managers and decision-makers to estimate the likely projected decline (%) in the mean annual streamflow, which is influenced by climate, and to quantify the drought severity corresponding to a possible decrease in P and an increase in PET.

A pro-active estimation of possible climate change scenarios and their adverse impact on runoff and drought spells would provide the opportunity to improve current decisions concerned with water allocations in time and space. Moreover, the proposed method allows decision-makers to take appropriate actions in advance to avoid the likelihood of adverse impacts of drought and climate change on multi-water users, particularly those in the agricultural sector. This timely tool is of high importance to the lower riparian example country, Iraq, which has become vulnerable to recent frequent drought events and upstream human-induced activities.

The suggested approach is of generic nature and has merits at national, regional and universal scales. At the national level, it supports water managers and other related stakeholders to take serious steps and actions to handle the anticipated reductions in runoff volume according to various scenarios of climate change and recurrent droughts. At the regional scale, the approach offers a common platform for riparian states for better coordination to reduce possible harmful environmental and socio-economic effects of shared water use in upstream countries on the downstream states. Correspondingly, at universal level, the approach can be applied to develop similar figures and estimate the possible reductions in annual runoff due to climate alterations and drought episodes.

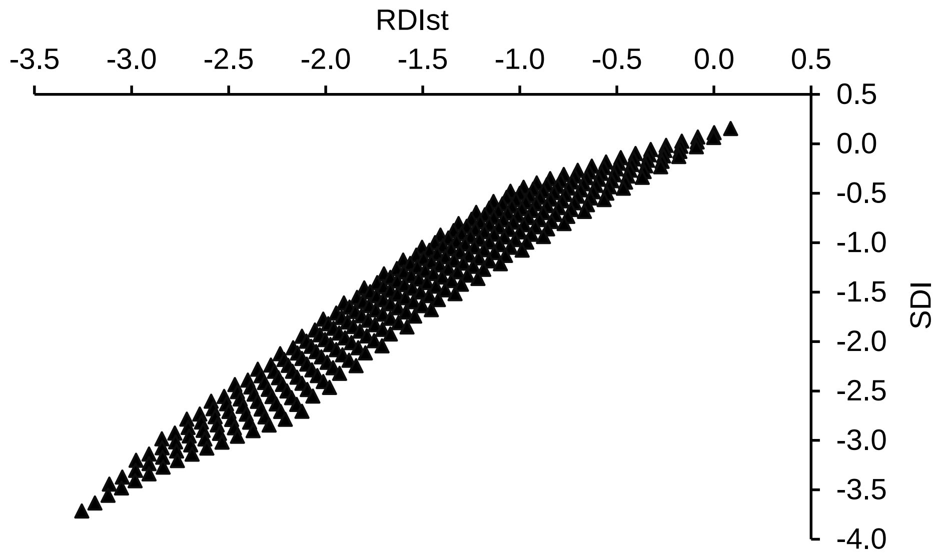

Figure 4-18: Relationship between the anticipated standardized Reconnaissance Drought Index (RDIst) and the Streamflow Drought Index (SDI) for the upper Diyala example basin.

4.5 Estimation of baseflow contribution to total runoff

4.5.1 Flow duration curve analysis for the upper basin

The proposed approach and the findings have been published in the following journal:

Al-Faraj, F. A. M., & Scholz, M. (2014c). Incorporation of the flow duration curve method within digital filtering algorithms to estimate the base flow contribution to total runoff. *Water Resources Management.* doi: 10.1007/s11269-014-0816-7

Findings obtained from the daily flow duration curve (DFDC) at the DHS revealed that the flows, which are ≥90% (Q90) and ≥50% (Q50) of the time, are 41 m^3/s and 108 m^3/s, respectively (Figure 4-7). The BFI (Q90/Q50) is 0.38 for the upper sub-basin, indicating that 38% of long-term total stream flow could be derived from groundwater discharge or other delayed shallow sub-surface flow.

4.5.2 Flow duration curve analysis for the combined upper and middle basins

Results extracted from the DFDC at the DDS show that the Q90 and Q50 flows, are 27 m^3/s and 87 m^3/s, respectively (Figure 4-9). The corresponding BFI is 0.31, indicating that the long-term proportion of groundwater represented 31% of the integrated runoff of the river basin measured at this site. Findings indicate that the BFI of the upper part of the basin (0.38) is relatively higher than the one estimated at the downstream site (0.31). This can be attributed to the differences between the time frames examined at each site and the bearing capacity of the aquifers of the middle reach of the basin, which may hold and subsequently release less water, reducing the BFI. However, more attention should be given to assess the characteristics of aquifers and understand the root cause behind such differences for improving management of groundwater resources.

4.5.3 Integrating flow duration curve analysis into digital filtering algorithms

Upper basin. Referring to Equation 2.1 of the digital filtering algorithm, results show that the filter parameter α with a value of 0.99732 produces a BFI that equates to the one derived from the flow duration curve analysis. The annual baseflow magnitudes over the hydrologic years 1955 to 1982 vary between 0.74 billion m^3

observed in 1960 and 5.52 billion m^3 measured in 1969. The corresponding annual baseflow varied between about 43 mm/year to about 308 mm/year. The long-term annual average baseflow volume and the corresponding standard deviation (stdev) are 2.08 billion m^3 and 0.91 billion m^3, respectively. The long-term mean annual baseflow and the corresponding stdev are estimated at approximately 116 mm/year and nearly 51 mm/year, respectively. The developed linear model expressed in Equation 4.7 shows the relationship between the isolated baseflow and the total runoff. A solid correlation coefficient *r* of 0.924 is observed.

$$B_f = 0.319R_t + 0.3348 \qquad \text{Equation 4.7}$$

where B_f is the isolated baseflow and R_t is the total runoff observed at the DHS.

The BFI values (Figure 4.18) ranged from 0.24 in 1963 to 0.54 in 1960. The long-term BFI and the corresponding stdev are 0.38 and 0.072, respectively. Findings reveal that about 61% of the annual BFI values fall between mean–stdev and mean+stdev. The coefficient of variation is 0.189.

As far as Equation 2.2 of the digital filtering algorithm is concerned, findings reveal that that the filter parameter α of 0.9949 generates a BFI that equates to the one extracted from the generated flow duration curve. The values of annual baseflow during the water years between 1955 and 1982 vary between 0.66 billion m^3 observed in 1960 and 5.45 billion m^3 measured in 1969. The corresponding annual baseflow varies between about 37 mm/year to nearly 305 mm/year. The long-term mean annual baseflow volume and the corresponding stdev are 2.07 billion m^3 and 0.90 billion m^3, respectively. The long-term mean annual baseflow and the corresponding stdev are computed at approximately 116 mm/year and about 50 mm/year, respectively.

The developed linear model (Equation 4.8) shows the relationship between the separated baseflow and the total runoff. A strong correlation coefficient r of 0.969 is obtained.

B_f =0.3316R_t+0.2616 Equation 4.8

where B_f is the isolated baseflow and R_t is the total runoff observed at the DHS.

The annual temporal variability of the computed BFI values (Figure 4-19) ranged from 0.28 in 1963 to 0.48 in 1960. The long-term BFI and the stdev are estimated at 0.38 and 0.047, respectively. Findings reveal that about 64% of the annual BFI values fall between mean–stdev and mean+stdev. The coefficient of variation is estimated at 0.124. A very robust correlation coefficient r of 0.986 is obtained between the isolated baseflow using the two digital filtering algorithms. The developed linear model is expressed in Equation 4.9.

$B_{f(Eq.2)} = 0.9778B_{f(Eq.1)} + 0.0422$ Equation 4.9

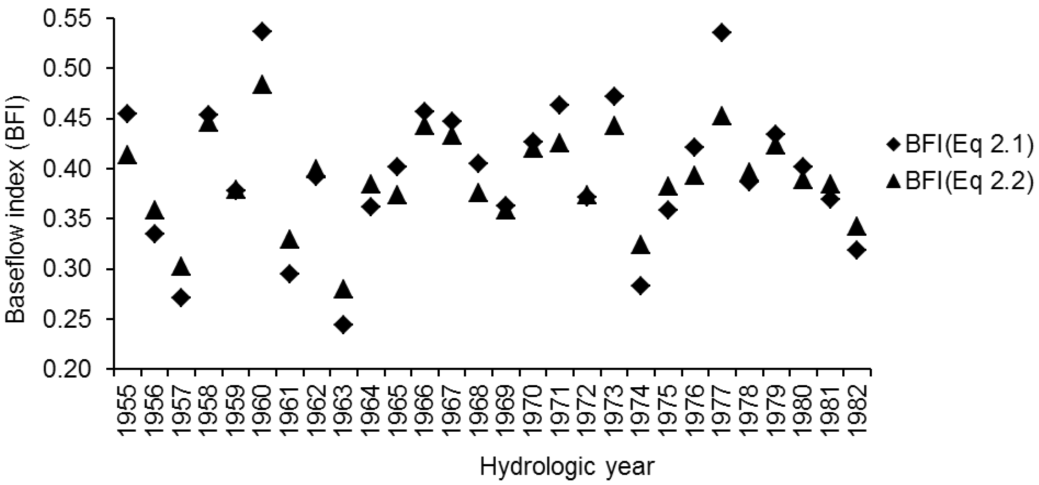

Figure 4-19: Annual variability of BFI using Equations 2.1 and 2.2 at the DHS.

Combined upper and middle basins. Results show that the filter parameter α of 0.99732 (Equation 2.1) produced a BFI equating to the one extracted from the developed flow duration curve. The annual baseflow magnitudes during the hydrologic years between 1931 and 1961 vary between 0.95 billion m^3 observed in 1948 and 2.60 billion m^3 measured in 1939. The long-term mean annual baseflow volume and the corresponding stdev are 1.69 billion m^3 and 0.50 billion m^3, respectively. The developed linear model expressed in Equation 4.10 shows the relationship between the isolated baseflow and the total runoff. A firm correlation coefficient *r* of 0.858 is observed.

$B_f = 0.1966 R_t + 0.6181$ Equation 4.10

where B_f is the isolated baseflow and R_t is the total runoff observed at the DDS.

The annual temporal changes of the BFI are displayed in Figure 4-19. The BFI values ranged from 0.23 in 1949 to 0.55 in 1947. The long-term BFI and the stdev are estimated at 0.31 and 0.0845, respectively. Findings reveal that about 81% of the annual BFI values fall between mean–stdev and mean+stdev. The coefficient of variation is 0.273.

As far as Equation 2.1 is concerned, findings reveal that that the optimal filter parameter α of 0.9949 generated a BFI that equates to the one extracted from the generated flow duration curve. The annual baseflow magnitudes during the water years between 1931 and 1961 vary between 0.81 billion m^3 observed in 1960 and 2.75 billion m^3 measured in 1939. The long-term mean annual baseflow volume and the stdev are estimated at 1.70 billion m^3 and 0.55 billion m^3, respectively. The developed linear model expressed in Equation 4.11 exhibits the relationship between the separated baseflow and the total runoff. A strong correlation coefficient *r* of 0.933 was obtained.

$B_f = 0.2345 R_t + 0.4143$ Equation 4.11

where B_f is the isolated baseflow and R_t is the total runoff observed at the DDS.

The annual temporal changes of the BFI are displayed in Figure 4-20. The BFI values ranged from 0.25 in 1949 to 0.48 in 1947. The long-term BFI and the stdev were estimated at 0.31 and 0.0593, respectively. Findings reveal that about 77% of the annual BFI values are between mean–stdev and mean+stdev. The coefficient of variation was found to be 5.224. The developed formula shows a very strong correlation coefficient r of 0.984. The corresponding linear model is expressed in Equation 4.12.

$$B_{f(Eq.2)} = 1.0789B_{f(Eq.1)} - 0.1305 \qquad \text{Equation 4.12}$$

Smakhtin (2001b) has proposed that the optimal filter parameter values normally fluctuate in the range between 0.985 and 0.995. Despite the range of the mean annual precipitation values (285 mm to 965 mm) of the examined basin, which falls within the limits mentioned by Smakhtin (2001b), the presented values of the filter parameter indicated an increase of the default value of α by about 7.7% (instead of 2.0%).

Results show that the presented filter parameter values of 0.99732 and 0.9949, which were derived from Equations 2.1 and 2.2, respectively, are the same for the upper basin, and the combined upper and middle basins. This indicates that the aquifers of the two basins have approximately similar characteristics.

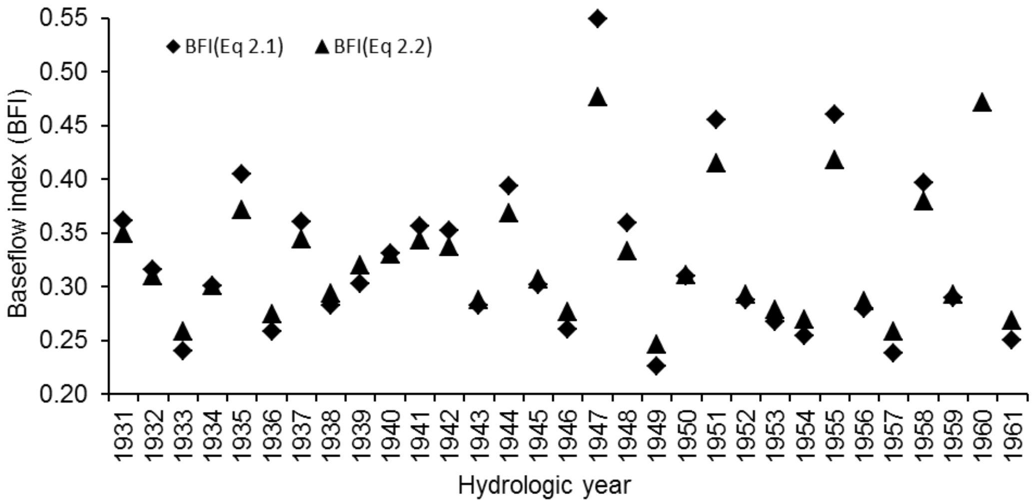

Figure 4-20: Annual variability of the BFI using Equations 2.1 and 2.2 at the DDS.

4.5.4 Cyclic analysis of the baseflow index

Upper basin. The seasonal variability of the BFI during wet and dry seasons is shown in Figure 4-21. Results indicate that the most notable pattern to emerge is an increase in BFI values between April and May, which appears to be robust. The BFI variability is generally of much lower magnitude and weaker during summer. Findings also indicate that the potential of the basin to release water from the groundwater storage and other delayed sources increases significantly at the beginning of April until it hits a peak by the end of May, remains fairly steady until the mid of July and gradually drops until the end of September.

This suggests that the period between April and July is the most fertile time window for releasing groundwater storage and contributing to total runoff. These findings demand the need to exploit groundwater without unduly affecting the essence of sustainable development taking into account the capability of the aquifers in yielding water over various timeframes. A baseflow duration curve can be developed to show the percentage of time at which a specific baseflow is equalled or exceeded. Moreover, the concept of sustainable pumping rate was recently implemented in areas facing conflicts in terms of managing groundwater resources (Singh, Bürger, & Cirpka, 2013) through the development of a numerical optimization model for the managed aquifer, thereby activating and deactivating wells in the examined aquifer.

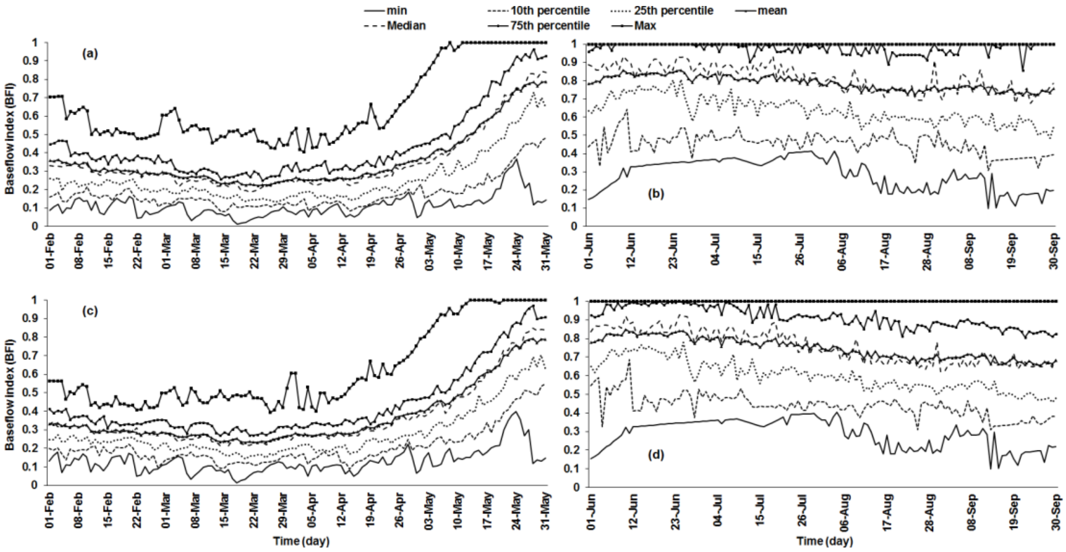

Figure 4-21: Seasonal variation of baseflow index (BFI) at the Derbandikhan hydrometric site during wet and dry seasons: (a) wet season (February to May) – flow duration curve (FDC) incorporated into Equation 2.1; (b) dry season (June to September) – FDC incorporated into Equation 2.1; (c) wet season (February to May) – FDC incorporated into Equation 2.2; and (d) dry season (June to September) – FDC incorporated into Equation 2.2.

Combined upper and middle basins. The seasonal changes of the BFI for the winter and summer seasons are shown in Figure 4-22. The BFI values rose between April and mid-July. The BFI variability generally depicts a higher magnitude of fluctuation during the summer period. Results also show that the watershed potential of discharging groundwater and other delayed sources started to increase at the beginning of April until it peaked in mid-July. The examination of results shows that despite the gradual drop in BFI values from mid-July until the end of

September, local minima and maxima were observed. Moreover, findings indicated that it took a relatively long period of time before the BFI values peaked.

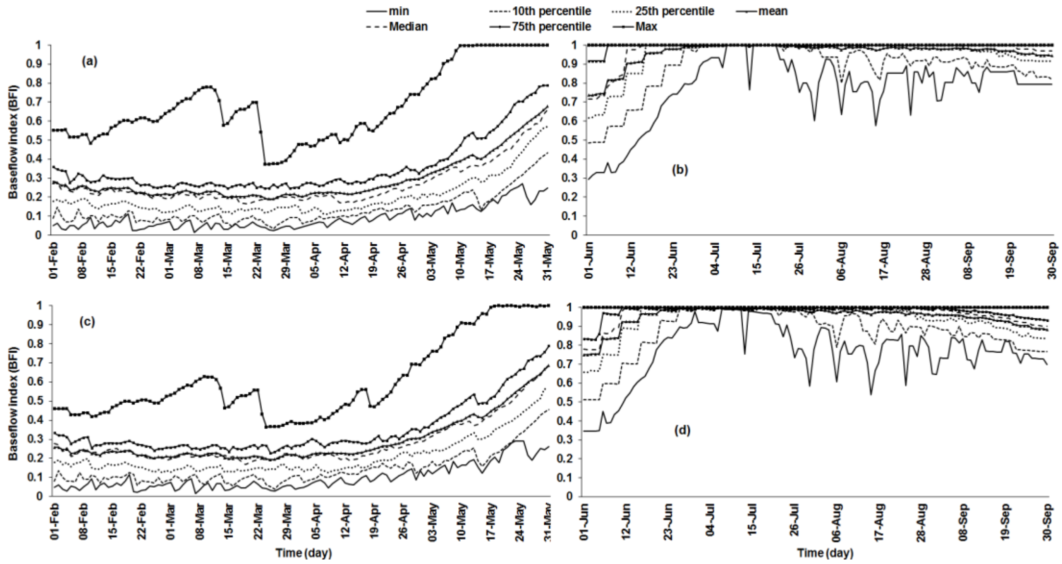

Figure 4-22: Seasonal variation of baseflow index (BFI) at Diyala discharge site during wet and dry seasons: (a) wet season (February to May) – flow duration curve (FDC) incorporated into Equation 2.1; (b) dry season (June to September) – FDC incorporated into Equation 2.1; (c) wet season (February to May) – FDC incorporated into Equation 2.2; and (d) dry season (June to September) – FDC incorporated into Equation 2.2.

4.5.5 Comparison between the upper basin, and the combined upper and middle basins

The drainage areas of the upper basin and the combined upper and middle basins are 17,900 km^2 and 29,800 km^2, respectively. Findings reveal that the long-term BFIs of the two examined basins are approximately close to each other; the upper part of the basin has a BFI value equal to 0.38, while the combined basin (including the upper portion of the basin with a drainage area of 17,900 km^2) has a BFI value of 0.31. The slight difference in BFI values could be attributed to the variance in the period examined for each basin. The time span for the upper basin is between 1955 and 1982 (28 years), while the time horizon for the combined basin covers the years 1931 to 1961 (31 years). Despite the fact that the drainage area of the upper basin represents 60% of the combined basin, the upper basin receives a significantly higher rate of precipitation. This may give more weight to the upper aquifers in terms of groundwater release and contribution to total runoff.

4.5.6 National and international relevance of the proposed method

Data from different countries can be contradictory largely because there are no unified standards for measuring hydrological changes. Moreover, each riparian state often treats water-related data as sensitive. The fact that cooperation between riparian countries is limited further impedes a consensus regarding the reliability of water data and the development of a common vision on shared water resources management. Upstream anthropogenic regulation can significantly affect the flow characteristics of the downstream country (Al-Faraj & Scholz, 2014a).

While some forms of regulation can affect the flow regimes of both surface and groundwater, only the impacts of upstream regulation on baseflow signatures are of concern in this study. In this regard, a new methodology has been proposed to overcome the drawbacks suffered by the digital filtering algorithms in estimating the baseflow contribution. This method provided reliable results, which can further be used in exploring the impact of upstream man-made activities on natural baseflow measured at the downstream state.

A double mass analysis can be conducted by assessing regulated and unregulated gauge sites to access the degree to which the current forms of regulation have affected the natural baseflow of the downstream state. Reliable data based on timely methodology can lead to a better understanding of the signature of the natural baseflow and explain how the damming of the river, diversion and water exploitation in the upstream riparian may change the flow paradigm of the baseflow of the lower riparian state. A solid approach that provides consistent results can put the downstream country in a stronger position while negotiating water issues with other upstream riparian states.

4.6 Isolating human-interventions and climate change alteration

This section has been submitted in

Al-Faraj, F., & Scholz, M. Impact of basin-wide dry climate conditions and non-climatic drivers: an isolation approach. *Journal of Water and Climate Change* (under consideration).

Results show that the long-term mean streamflow observed at the DHS of the unimpaired and impaired streamflow paradigms, are about 173 m^3/s and 131 m^3/s, respectively. This suggests that the artificially-influenced streamflow period had seen a flow reduction of approximately 25%. The 25th, 50th, and the 75th percentiles were dropped by about 47%, 33% and 19%, respectively. The streamflow reductions can be attributed to the collective impacts of anthropogenic pressures on the river basin in the upstream riparian state and basin-wide dry climate conditions.

4.6.1 Upper basin

The 89-year SDI time series between 1925 and 2013 at the DHS for successive non-overlapping 1-month time intervals and for four overlapping reference periods within each hydrologic year (October-December, October-March, October-June, and October-September (i.e. one complete hydrologic year)) are shown in Figure 4-23 and Figure 4-24, respectively. Irregular frequent droughts of varying severity and duration are recognized between 1925 and 2013. Findings from the 1-month SDI time series reveal that drought spells are observed for (a) about 44% of the pre-impact period (1925-1982), (b) nearly 40% of the transition period (1983 to 2003) during which, limited river regulation measures were put in place, (c) approximately 92% of the time period between 1999 and 2013, and (d) nearly 93% of the time between 2004 and 2013.

The period between 1925 and 1998 shows a significant temporal disparity in SDI magnitudes punctuated by non-drought spells. This can be explained by the typical characteristics of the hydrologic regime dominated by a rainy period between October and May, and a non-rainy period between June and September. The dry period may span over one complete hydrologic year or several water years such as 1948, 1958 and 1960. Dealing with the four reference time intervals, prolonged droughts of mild to moderate severity are detected over five successive years between 1928 and 1932 with SDI ranging from –0.05 to –1.12. Between 1933 and 1946, only two years of mild to moderate drought spells were observed in 1935 and 1944 with SDI ranges between –0.43 and –1.08. Between 1947 and 1957, mild to moderate droughts are recorded in 1947, 1948, 1951, 1955 and 1956. The SDI values fell between –0.03 and –1.66. Moderate to mild drought episodes are sustained for the period from 1958 to 1962 with some signs of short-term extreme drought spells. The SDI values ranged from –0.34 to –2.49. Short-term droughts are registered for the hydrologic years 1963-1990, followed by a mild drought in 1991. Moderate to mild droughts are also recorded in 1997 with SDI ranging between –0.53 to –1.18.

Findings revealed that droughts are frequently detected between 1999 and 2013. Droughts of extreme severity are acknowledged for the hydrologic years 2000, 2001, 2008 and 2009. No tangible artificial regulations and hydraulic water diversions were implemented and commissioned between 1925 and 1982 in the upstream riparian state. Likewise, limited hydraulic regulation works and water exploitation schemes in the upper part of the basin were observed between 1983 and 2004 (Al-Faraj & Scholz, 2014a,b). Hence, the droughts can be assigned mainly to the abnormality of precipitation. This is supported by the findings of the SPI values (Table 4-19) for four time intervals (i.e. 3-, 6-, 9- and 12-months).

A close examination of Table 4-19 reveals that the water years of 1984, 1989, 1991, 1996, 1997 and 1999-2001 had noticeable drought spells for various time intervals over the examined meteorological stations. Moreover, results indicate that the drought spells were not limited to a number of stations but were observed in all examined meteorological stations. This suggests that the entire watershed is frequently prone to drought episodes, in particular from 1999 onwards.

Outstanding river regulation arrangements were put in place between 2004 and 2013, twinned with extreme basin-wide dry climate conditions, which span the years 2008-2009. The SDI peaked at –2.72 in 2009. According to SDI magnitudes, the successive drought periods 1999-2001 and 2008-2009 were the most influential to agriculture and water resources of the downstream country. Between 2010 and 2013, the severity of the drought ranged from severe to mild. The disparity in severity and duration of drought spells, which extended for the period 2004-2013, is attributed to collective impacts, including precipitation anomalies, the volume of water abstraction, diversion across the main river corridor and its tributaries, and the operational practices and management of the upstream reservoirs.

4.6.2 Upper and middle combined basins

The SDI time series between 1925 and 1961 at the DDS for 1-month time intervals and four reference periods are shown in Figure 4-25 and Figure 4-26, respectively. Findings from the non-overlapping SDI of 1-month time intervals revealed that drought spells are perceived for about 54% of the pre-river regulation period (1925-1961). No non-drought spells were detected for the hydrologic years 1931, 1932, 1935 and 1948. Extreme droughts are observed in February 1948, February-April 1960, July 1960 and October 1961. The 1-month SDI peaked at –2.80 in March 1960.

Extreme drought spell characteristics are recognized for the years 1948 and 1960 with the SDI ranging from –2.09 to –2.53. Mild and moderate drought spells lasted for about 7% and 39% of the observed time period, respectively. In comparison, the maximum time during which extreme and severe drought spells were observed was about 7%. The severity and duration of droughts between 1931 and 1961 were due to precipitation deviations compared to normal conditions.

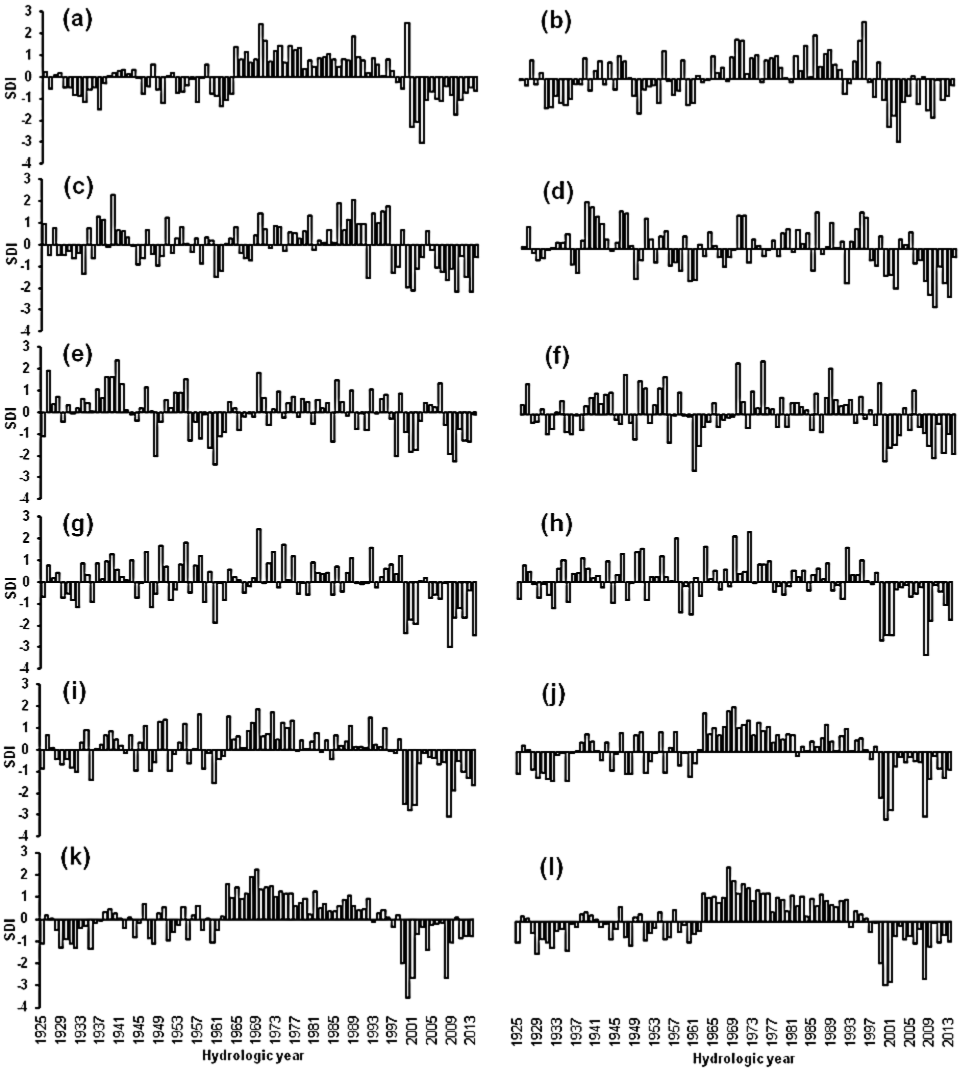

Figure 4-23: Temporal variation of the stream flow drought index (SDI) between 1925 and 2013 at the Derbandikhan hydrometric site for (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May, (i) June, (j) July, (k) August and (l) September.

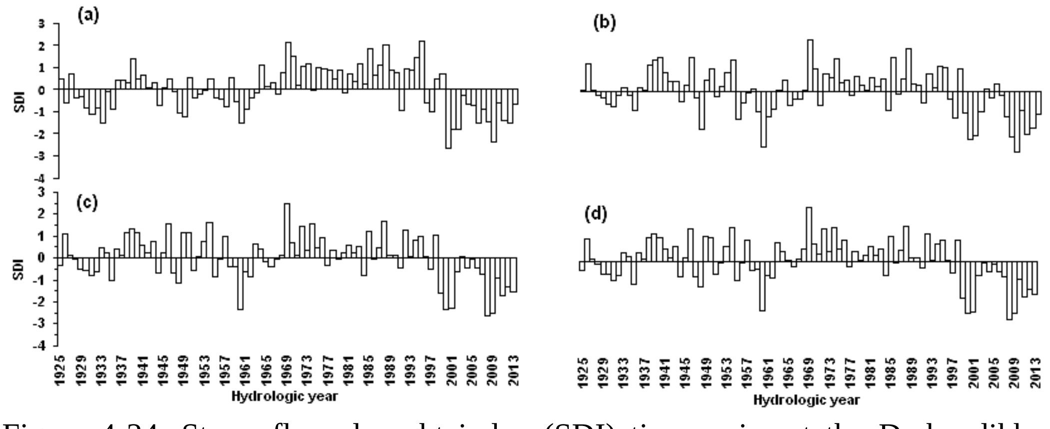

Figure 4-24: Streamflow drought index (SDI) time series at the Derbandikhan hydrometric site for the over lapping four reference periods; (a) SDI for 3 months, (b) SDI for 6 months, (c) SDI for 9 months and (d) SDI for 12 months.

Table 4-19: Standardized precipitation index (SPI) analysis for four reference periods for all examined meteorological stations (Table 4-19 continuous on next page).

Year	**SPI**																			
	Ghorveh				Sanandaj				Ravansar				Saghez				Derbandikhan			
	3	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**
1981	0.63	1.56	1.38	1.39	0.47	1.24	0.96	0.96	0.69	1.46	1.51	1.52	0.60	0.67	0.55	0.53	0.66	1.34	1.39	1.40
1982	**-0.15**	1.52	1.54	1.56	**-0.15**	1.24	1.27	1.28	0.19	**-0.23**	0.29	0.31	**-0.17**	0.40	0.54	0.51	0.34	0.75	0.98	1.00
1983	1.22	0.95	0.92	0.92	1.25	1.04	0.97	0.96	0.73	0.41	0.28	0.28	1.52	1.40	1.44	1.43	0.71	0.72	0.63	0.63
1984	0.34	0.57	0.80	0.80	0.19	0.38	0.74	0.73	**-0.39**	**-0.09**	0.17	0.17	**-0.42**	**-0.68**	**-0.01**	**-0.06**	**-0.28**	**-0.86**	**-0.50**	**-0.51**
1985	1.39	1.44	1.25	1.26	1.40	1.42	1.03	1.03	1.63	1.77	1.66	1.68	0.83	0.91	0.80	0.78	1.32	1.35	1.35	1.35
1986	0.40	0.17	0.55	0.54	0.22	0.03	0.63	0.62	0.56	0.36	0.59	0.59	0.51	**-0.25**	0.28	0.24	0.51	0.15	0.32	0.31
1987	0.55	0.44	0.18	0.17	0.45	0.32	**-0.06**	**-0.08**	0.84	1.02	0.60	0.60	0.80	0.67	0.26	0.24	0.74	0.49	0.28	0.28
1988	0.86	0.85	0.65	0.64	1.71	1.85	1.37	1.38	1.39	1.66	1.20	1.21	0.97	1.55	1.09	1.19	1.43	2.03	1.69	1.70
1989	**-0.19**	**0.23**	**-0.12**	**-0.13**	**-0.07**	0.42	**-0.28**	**-0.30**	**-0.33**	**-0.23**	**-0.55**	**-0.57**	**-0.35**	**-0.31**	**-0.78**	**-0.82**	0.83	0.55	0.21	0.21
1990	0.60	0.37	0.11	0.10	0.34	**-0.11**	**-0.40**	**-0.42**	0.93	0.65	0.17	0.16	**-0.12**	**-0.02**	**-0.12**	**-0.17**	0.20	0.41	0.35	0.35
1991	**-1.36**	**-0.85**	**-0.92**	**-0.95**	**-1.94**	**-1.11**	**-1.20**	**-1.24**	**-2.12**	**-0.68**	**-0.96**	**-0.98**	**-1.14**	**-0.71**	**-0.63**	**-0.69**	**-0.22**	**-0.32**	**-0.65**	**-0.66**
1992	0.75	0.93	0.86	0.86	0.32	0.25	0.21	0.20	0.50	0.65	0.74	0.74	1.37	1.14	1.37	1.36	0.80	0.33	0.25	0.25
1993	0.00	**-0.33**	0.17	0.16	**-0.35**	**-0.80**	**-0.28**	**-0.30**	**-0.21**	**-0.55**	**-0.16**	**-0.17**	0.13	0.27	0.80	0.78	0.27	**-0.24**	0.20	0.20
1994	0.61	0.24	0.11	0.11	1.28	1.31	1.07	1.10	0.67	0.66	0.22	0.21	1.78	1.84	1.48	1.51	0.34	**-0.18**	**-0.25**	**-0.26**
1995	2.20	1.06	1.29	1.30	1.74	1.01	1.79	1.81	1.67	1.17	1.28	1.28	1.78	1.07	1.34	1.34	0.13	**-0.70**	**-0.29**	**-0.28**
1996	**-2.41**	**-0.88**	**-0.52**	**-0.54**	**-1.72**	**-0.86**	**-0.27**	**-0.29**	**-1.72**	**-0.39**	0.07	0.09	**-1.89**	**-0.38**	**-0.11**	**-0.02**	**-1.46**	**-0.88**	**-0.89**	**-0.90**
1997	**-1.36**	**-1.59**	**-0.98**	**-1.01**	**-0.01**	**-0.43**	**-0.07**	**-0.09**	**-1.28**	**-1.18**	**-1.06**	**-1.09**	**-1.71**	**-0.32**	**-0.22**	**-0.19**	**-0.47**	**-0.90**	**-0.94**	**-0.95**
1998	0.38	0.99	0.87	0.89	0.49	1.23	0.85	0.87	1.13	1.30	1.15	1.17	0.20	0.89	0.73	0.73	0.80	0.83	0.66	0.66
1999	**-2.01**	**-1.44**	**-1.45**	**-1.38**	**-2.49**	**-2.02**	**-2.2**	**-2.16**	**-1.48**	**-1.38**	**-1.64**	**-1.64**	**-1.61**	**-1.22**	**-1.74**	**-1.61**	**-3.74**	**-1.74**	**-1.95**	**-1.97**

Year	**SPI**																			
	Ghorveh				Sanandaj				Ravansar				Saghez				Derbandikhan			
	3	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**
2000	**-1.48**	**-1.83**	**-2.02**	**-2.06**	**-1.10**	**-0.84**	**-1.06**	**-1.06**	**-1.03**	**-1.68**	**-1.55**	**-1.58**	**-0.72**	**-0.91**	**-0.98**	**-0.92**	**-0.73**	**-1.43**	**-1.61**	**-1.61**
2001	0.01	**-0.78**	**-1.10**	**-1.03**	**-0.42**	**-1.56**	**-1.51**	**-1.42**	**-0.72**	**-0.93**	**-1.11**	**-1.09**	**-0.19**	**-0.90**	**-1.12**	**-1.00**	**-0.35**	**-1.26**	**-1.51**	**-1.50**
2002	**-0.41**	**-0.53**	**-0.23**	**-0.25**	**-0.70**	**-0.91**	**-0.45**	**-0.47**	**-0.56**	**-1.14**	**-0.52**	**-0.54**	**-0.04**	0.04	0.06	0.02	0.34	1.08	1.08	1.08
2003	**-0.16**	**-0.39**	**-0.67**	**-0.70**	0.25	**-0.34**	**-0.33**	**-0.35**	0.40	0.14	0.02	0.01	0.84	0.83	0.64	0.60	0.94	0.92	0.80	0.80
2004	0.77	**-0.14**	0.08	0.07	0.16	**-0.30**	**-0.01**	0.04	0.55	**-0.11**	0.44	0.44	0.01	0.08	0.18	0.19	0.30	0.37	0.42	0.42
2005	**-0.01**	0.75	0.46	0.45	**-0.24**	0.17	**-0.26**	**-0.28**	**-0.54**	0.62	0.14	0.13	0.26	0.02	**-0.06**	**-0.02**	0.33	0.79	0.57	0.57
2006	**-0.54**	0.56	0.59	0.58	**-0.76**	**-0.20**	**-0.20**	**-0.22**	**-1.15**	0.15	0.33	0.32	**-0.54**	0.17	0.22	0.18	**-0.53**	0.01	0.24	0.24
2007	0.35	**-0.43**	**-0.03**	**-0.05**	0.54	0.22	0.68	0.69	**-0.01**	**-0.76**	**-0.16**	**-0.18**	0.48	**-0.23**	**-0.21**	**-0.21**	**-0.39**	**-0.63**	0.04	0.03
2008	**-1.15**	**-2.15**	**-2.59**	**-2.60**	**-1.29**	**-1.94**	**-2.41**	**-2.43**	**-1.25**	**-2.32**	**-2.93**	**-2.90**	**-1.38**	**-1.95**	**-2.49**	**-2.52**	**-1.84**	**-2.05**	**-2.32**	**-2.27**
2009	**-0.24**	**-1.22**	**-1.21**	**-1.15**	**-0.07**	**-0.86**	**-0.85**	**-0.81**	0.22	**-0.67**	**-0.83**	**-0.76**	**-1.37**	**-2.01**	**-1.45**	**-1.51**	**-0.63**	**-1.5**	**-1.28**	**-1.29**
2010	0.52	**-0.05**	0.10	0.09	0.62	0.15	0.29	0.28	0.76	0.35	0.65	0.65	**-0.45**	**-1.98**	**-1.78**	**-1.85**	0.76	0.59	0.79	0.79

Year	SPI																			
	Dokan				Marivan				Sarpolzahab				Khanaqin				Eslamabad			
	3	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**
1981	0.20	0.72	0.63	0.63	0.41	0.75	0.52	0.51	0.59	1.37	1.20	1.20	0.49	1.34	1.14	1.14	0.63	1.56	1.38	1.39
1982	0.34	0.33	0.62	0.62	0.15	0.13	0.54	0.56	0.61	0.48	0.79	0.79	0.52	0.60	0.87	0.87	**-0.15**	1.52	1.54	1.56
1983	0.83	0.23	0.27	0.27	0.84	0.26	0.15	0.14	0.94	0.42	0.33	0.33	0.89	0.39	0.32	0.32	1.22	0.95	0.92	0.92
1984	**-0.77**	**-1.51**	**-1.50**	**-1.52**	**-0.54**	**-1.12**	**-0.65**	**-0.67**	**-0.32**	**-0.05**	**-0.25**	**-0.25**	**-0.43**	**-0.39**	**-0.48**	**-0.48**	0.34	0.57	0.80	0.80
1985	1.04	1.01	0.82	0.81	1.00	0.84	0.70	0.69	1.83	1.86	1.92	1.92	1.73	1.89	1.81	1.81	1.39	1.44	1.25	1.26
1986	0.44	**-0.29**	**-0.05**	**-0.06**	**-0.15**	**-0.45**	**-0.13**	**-0.14**	0.68	**-0.16**	0.49	0.49	0.58	**-0.21**	0.13	0.13	0.40	0.17	0.55	0.54
1987	0.46	0.42	0.11	0.11	0.28	0.05	**-0.11**	**-0.12**	0.20	0.38	0.01	0.01	0.12	0.12	**-0.12**	**-0.12**	0.55	0.44	0.18	0.17
1988	1.60	2.13	1.95	1.96	1.27	1.76	1.50	1.49	1.63	1.73	1.47	1.47	1.22	1.21	1.15	1.15	0.86	0.85	0.65	0.64

Year	SPI																			
	Dokan				Marivan				Sarpolzahab				Khanaqin				Eslamabad			
	3	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**
1989	0.48	**-0.15**	**-0.50**	**-0.50**	0.23	**-0.14**	**-0.69**	**-0.70**	**-0.27**	0.14	**-0.32**	**-0.33**	**-0.29**	**-0.96**	**-1.25**	**-1.25**	**-0.19**	0.23	**-0.12**	**-0.13**
1990	0.64	0.24	0.15	0.15	0.19	**-0.11**	**-0.27**	**-0.28**	0.79	1.42	1.13	1.13	**-0.17**	0.57	0.46	0.46	0.60	0.37	0.11	0.1
1991	**-0.46**	0.18	**-0.02**	**-0.03**	**-0.71**	0.02	**-0.24**	**-0.25**	**-0.76**	0.12	**-0.18**	**-0.18**	**-1.44**	0.14	**-0.02**	**-0.02**	**-1.36**	**-0.85**	**-0.92**	**-0.95**
1992	0.97	1.42	1.34	1.34	1.71	2.17	1.97	1.97	0.68	1.07	0.96	0.96	0.67	0.91	0.69	0.69	0.75	0.93	0.86	0.86
1993	0.70	0.10	0.84	0.84	0.42	**-0.07**	0.22	0.21	0.12	**-0.56**	**-0.10**	**-0.10**	**-0.29**	**-0.48**	0.23	0.23	0.00	**-0.33**	0.17	0.16
1994	0.48	0.63	0.64	0.69	0.96	1.13	1.05	1.06	0.54	0.32	0.31	0.31	0.53	0.18	0.12	0.12	0.61	0.24	0.11	0.11
1995	1.34	1.07	1.41	1.43	1.54	0.99	1.62	1.65	1.40	0.53	0.93	0.94	1.63	1.22	1.52	1.52	2.20	1.06	1.29	1.30
1996	**-1.77**	**-0.08**	**-0.06**	**-0.06**	**-1.59**	**-0.23**	0.13	0.13	**-1.06**	**-0.20**	**-0.32**	**-0.33**	**-0.64**	0.16	0.20	0.20	**-2.41**	**-0.88**	**-0.52**	**-0.54**
1997	**-0.68**	**-0.49**	**-0.56**	**-0.56**	**-1.02**	**-0.56**	**-0.24**	**-0.25**	**-1.00**	**-0.73**	**-0.72**	**-0.73**	**-1.02**	**-0.37**	**-0.24**	**-0.24**	**-1.36**	**-1.59**	**-0.98**	**-1.01**
1998	1.25	1.44	1.21	1.22	0.57	1.15	0.83	0.86	1.10	1.46	1.09	1.09	1.28	1.66	1.33	1.33	0.38	0.99	0.87	0.89
1999	**-2.39**	**-1.61**	**-1.79**	**-1.79**	**-3.08**	**-2.08**	**-2.18**	**-2.19**	**-1.56**	**-1.00**	**-1.43**	**-1.39**	**-1.41**	**-1.01**	**-1.22**	**-1.21**	**-2.01**	**-1.44**	**-1.45**	**-1.38**
2000	**-0.84**	**-1.11**	**-1.33**	**-1.34**	**-0.83**	**-0.97**	**-1.14**	**-1.08**	**-1.33**	**-1.80**	**-2.06**	**-2.08**	**-1.35**	**-2.07**	**-2.26**	**-2.26**	**-1.48**	**-1.83**	**-2.02**	**-2.06**
2001	**-0.49**	**-0.69**	**-0.93**	**-0.92**	**-0.26**	**-1.47**	**-1.71**	**-1.67**	0.86	0.33	**-0.03**	**-0.03**	1.45	1.03	0.74	0.74	0.01	**-0.78**	**-1.10**	**-1.03**
2002	0.34	0.03	0.15	0.14	0.52	0.42	0.37	0.36	0.02	**-0.30**	0.01	0.01	**-0.22**	0.38	0.59	0.59	**-0.41**	**-0.53**	**-0.23**	**-0.25**
2003	0.61	0.58	0.41	0.41	0.95	1.30	1.09	1.09	0.14	**-0.23**	**-0.28**	**-0.28**	0.17	**-0.76**	**-0.76**	**-0.76**	**-0.16**	**-0.39**	**-0.67**	**-0.70**
2004	0.29	0.57	0.68	0.67	0.16	0.15	0.50	0.49	**-0.36**	0.29	0.15	0.15	0.48	**-0.05**	**-0.07**	**-0.07**	0.77	**-0.14**	0.08	0.07
2005	0.23	0.47	0.41	0.40	0.15	0.43	0.14	0.17	**-1.79**	**-0.64**	**-0.06**	**-0.07**	0.08	0.31	0.17	0.17	**-0.01**	0.75	0.46	0.45
2006	**-1.52**	**-0.33**	**-0.06**	**-0.06**	**-0.87**	**-0.14**	**-0.05**	**-0.06**	**-0.95**	**-1.20**	**-0.67**	**-0.68**	**-1.59**	**-1.14**	**-0.94**	**-0.94**	**-0.54**	0.56	0.59	0.58
2007	0.04	**-0.42**	**-0.27**	**-0.28**	**-0.14**	**-0.82**	**-0.30**	**-0.31**	**-2.04**	**-1.91**	**-2.43**	**-2.44**	**-1.10**	**-0.57**	**-0.17**	**-0.17**	0.35	**-0.43**	**-0.03**	**-0.05**
2008	**-2.11**	**-2.06**	**-2.31**	**-2.25**	**-1.39**	**-1.71**	**-2.12**	**-2.12**	**-0.14**	**-1.23**	**-1.25**	**-1.19**	**-2.19**	**-2.31**	**-2.55**	**-2.56**	**-1.15**	**-2.15**	**-2.59**	**-2.60**
2009	**-1.10**	**-2.31**	**-1.78**	**-1.80**	**-0.97**	**-1.49**	**-1.43**	**-1.45**	0.46	**-0.20**	0.70	0.70	0.43	**-0.88**	**-0.86**	**-0.86**	**-0.24**	**-1.22**	**-1.21**	**-1.15**
2010	0.13	**-0.45**	**-0.45**	**-0.46**	0.48	**-0.19**	**-0.04**	**-0.06**	**-0.95**	**-1.71**	**-1.35**	**-1.36**	**-0.07**	**-0.88**	**-0.46**	**-0.46**	0.52	**-0.05**	0.10	0.09

Year	SPI											
	Sulaimaniya				Khalis				Baghdad			
	3	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**
1981	**-0.08**	0.56	0.37	0.37	0.51	0.97	0.96	0.92	1.05	1.13	0.78	0.78
1982	**-0.04**	0.03	0.44	0.46	**-0.64**	0.3	0.98	0.94	**-0.45**	0.42	0.98	0.98
1983	0.96	0.49	0.32	0.32	0.82	0.57	0.92	0.88	0.09	**-0.69**	**-0.77**	**-0.77**
1984	**-1.01**	**-1.81**	**-1.17**	**-1.18**	**-0.83**	**-0.49**	**-0.71**	**-0.77**	**-1.00**	**-0.39**	**-0.52**	**-0.53**
1985	0.85	0.72	0.59	0.59	0.89	1.20	0.82	0.78	0.90	0.48	0.13	0.13
1986	0.22	**-0.30**	**-0.04**	**-0.05**	0.02	0.03	1.71	1.68	0.09	0.73	1.31	1.31
1987	0.53	0.04	**-0.15**	**-0.16**	0.01	**-0.78**	**-0.92**	**-0.97**	0.05	**-1.52**	**-1.74**	**-1.74**
1988	1.02	1.51	1.30	1.30	0.46	0.80	1.00	0.96	**-0.41**	0.83	1.01	1.01
1989	0.35	**-0.23**	**-0.80**	**-0.81**	0.57	0.64	0.23	0.29	1.02	1.22	0.75	0.75
1990	0.20	**-0.06**	**-0.23**	**-0.24**	1.42	0.03	**-0.34**	**-0.40**	1.25	1.25	0.78	0.78
1991	**-0.58**	**-0.38**	**-0.16**	**-0.16**	0.03	2.03	1.51	1.49	0.59	0.26	**-0.14**	**-0.14**
1992	1.80	2.20	2.01	2.00	0.52	0.32	**-0.05**	**-0.10**	**-0.09**	**-0.65**	**-0.84**	**-0.84**
1993	0.74	0.02	0.77	0.76	1.73	2.15	1.69	1.98	0.68	1.62	2.10	2.10
1994	0.72	0.77	0.57	0.59	**-0.05**	**-0.86**	**-1.15**	**-0.52**	**-0.86**	**-0.16**	**-0.36**	**-0.34**
1995	1.30	0.98	1.38	1.42	0.78	1.17	0.99	0.96	1.89	1.27	1.07	1.07
1996	**-1.83**	0.00	0.11	0.10	**-0.39**	**-0.65**	**-0.90**	**-0.95**	**-0.10**	0.40	0.33	0.33
1997	**-0.34**	**-0.09**	**-0.12**	**-0.13**	**-0.76**	**-1.71**	**-1.66**	**-1.53**	**-1.75**	**-2.25**	**-2.18**	**-2.18**
1998	0.88	1.40	1.13	1.12	2.02	1.63	1.15	1.11	2.05	1.81	1.37	1.37
1999	**-3.27**	**-2.48**	**-2.80**	**-2.81**	**-0.23**	**-0.83**	**-1.14**	**-1.20**	**-0.14**	**-1.05**	**-1.38**	**-1.38**
2000	**-0.81**	**-1.36**	**-1.57**	**-1.56**	0.56	**-0.25**	**-0.48**	**-0.53**	0.01	**-1.08**	**-1.15**	**-1.15**
2001	0.09	**-0.49**	**-0.80**	**-0.79**	**-0.36**	**-0.44**	**-0.55**	**-0.61**	0.28	**-0.13**	0.07	0.07
2002	0.01	0.30	0.38	0.38	**-0.41**	0.04	0.36	0.32	**-1.41**	**-1.55**	**-0.50**	**-0.50**

Year	SPI											
	Sulaimaniya				Khalis				Baghdad			
	3	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**
2003	0.89	1.10	0.78	0.77	**-0.90**	**-0.90**	**-0.88**	**-0.94**	0.16	**-0.41**	**-0.47**	**-0.47**
2004	0.52	0.60	0.67	0.66	**-0.03**	**-0.83**	**-0.73**	**-0.79**	0.56	0.91	0.75	0.75
2005	**-0.12**	0.06	**-0.15**	**-0.16**	**-0.58**	**-0.26**	**-0.43**	**-0.49**	0.12	**-0.43**	**-0.57**	**-0.57**
2006	**-1.17**	**-0.29**	0.25	0.25	**-2.23**	0.24	0.59	0.55	**-1.94**	0.20	0.80	0.80
2007	**-0.57**	**-0.81**	**-0.37**	**-0.38**	**-1.16**	**-0.55**	**-0.02**	**-0.07**	**-0.16**	0.20	0.49	0.49
2008	**-0.75**	**-1.29**	**-1.70**	**-1.69**	**-2.64**	**-1.94**	**-2.16**	**-2.23**	**-2.33**	**-0.81**	**-1.18**	**-1.18**
2009	**-0.67**	**-1.53**	**-1.37**	**-1.32**	0.98	**-0.46**	**-0.51**	**-0.49**	0.11	**-0.72**	**-0.73**	**-0.73**
2010	0.59	0.36	0.42	0.42	0.05	**-1.23**	**-0.29**	**-0.27**	**-0.19**	**-0.86**	**-0.19**	**-0.19**

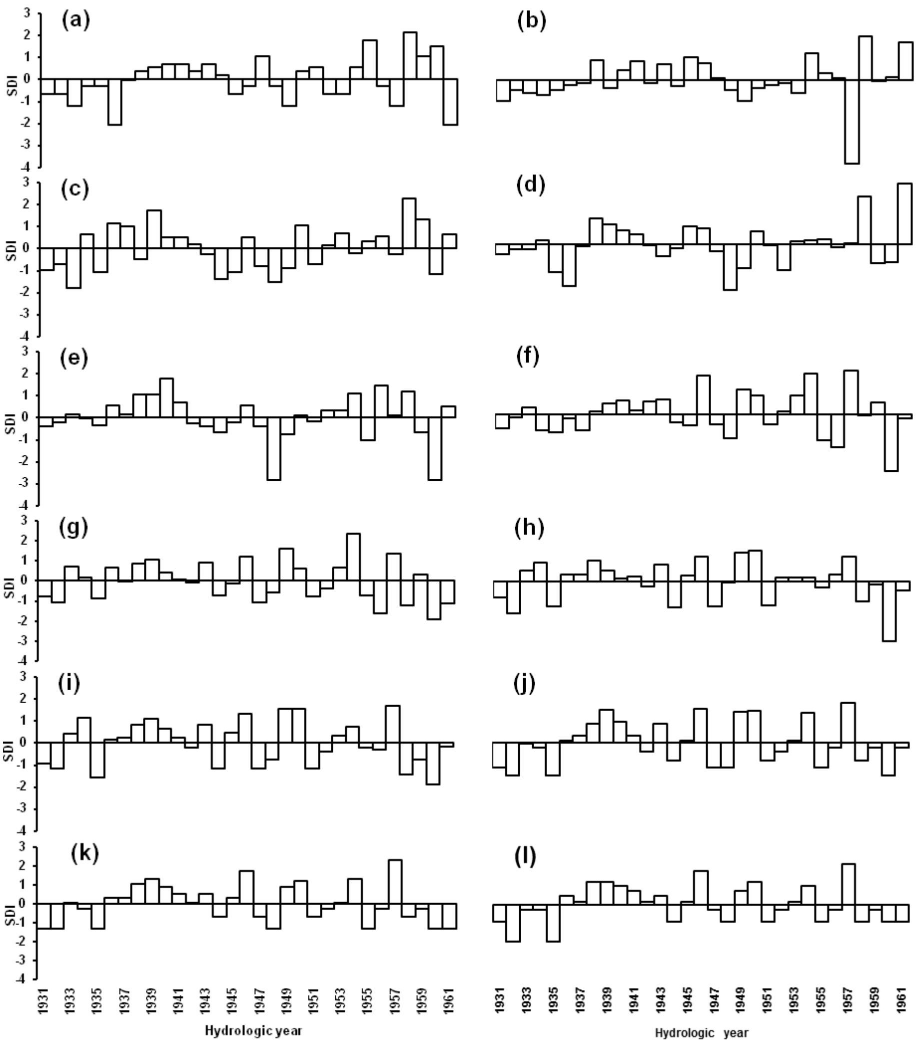

Figure 4-25: Temporal variation of the stream flow drought index (SDI) between 1925 and 1961 at the Diyala discharge site for (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May, (i) June, (j) July, (k) August and (l) September.

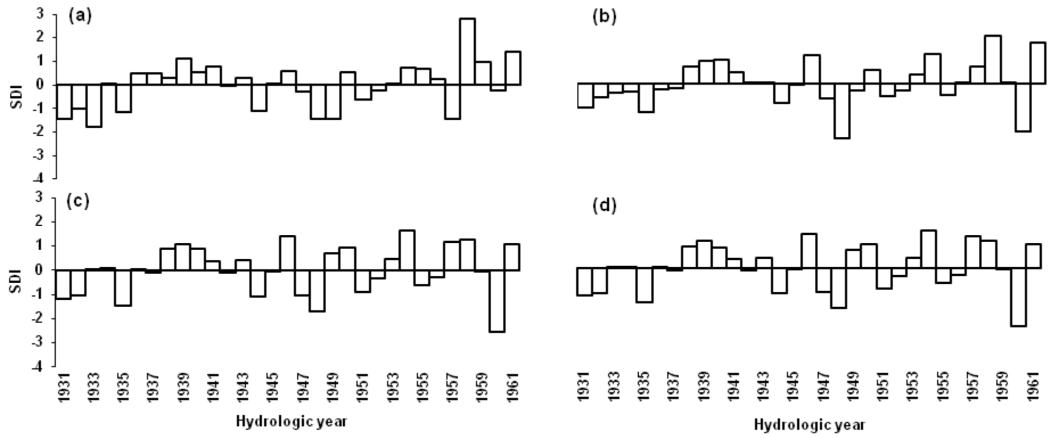

Figure 4-26: Streamflow drought index (SDI) time series at the Diyala discharge site for the overlapping four referenced periods; (a) SDI for 3 months, (b) SDI for 6 months, (c) SDI for 9 months and (d) SDI for 12 months.

The SDI and the SPI values have clearly indicated that the basin has recurrently suffered from meteorological and hydrological droughts. Since 2004, the hydrological drought observed in the lower riparian country has been considerably governed by basin-wide dry conditions and anthropogenic-induced river modifications in the upper riparian state.

The calculated 70-percentile monthly stream flows ranged from 22.5 m^3/s (September) to 264.1 m^3/s (April); see Figure 4-27. Results given in Table 4-20 show that the proportion of increase in standard deviation of the ratios ranged from the minimum estimated at 5.3 in February to the peak estimated at 115.7 in July. A rise is observed between April and October as well as in January, followed by December and November. February and March indicated the lowest average estimated value of 6%.

The increase in monthly standard deviations from the pre- to the post-regulation condition can be explained by upstream intense damming arrangements and significant consumptions of water and diversion measures. Findings disclose that the upstream river regulation schemes considerably reduced the water available for the downstream country. The relative impact ranged from a minimum value of 5% in February to the highest value of 54% in July. The average relative impacts between April and October and between November and March were about 46% and 17%, respectively.

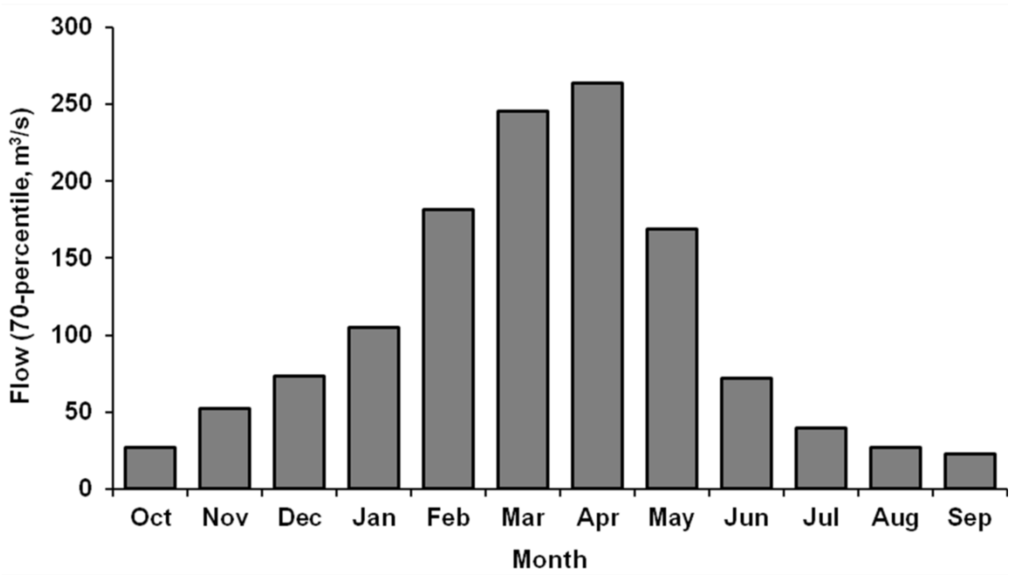

Figure 4-27: Monthly threshold levels based on 70-percentiles.

Table 4-20: The proportion of increase in standard deviation of the ratios.

Month	Pre-regulation %	Post-regulation %	Difference	% increase
Oct	14.7	26.3	11.6	79.0
Nov	15.4	18.7	3.3	21.6
Dec	14.2	18.6	4.4	31.3
Jan	16.2	23.3	7.1	43.4
Feb	21.2	22.3	1.1	5.3
Mar	19.2	20.5	1.3	6.6
Apr	14.2	27.4	13.2	92.6
May	17.1	30.5	13.4	78.0
Jun	15.7	27.7	12.0	76.8
Jul	14.3	30.9	16.6	115.7
Aug	17.4	27.8	10.4	60.1
Sep	15.4	29.6	14.2	91.9

4.7 Drought characteristics and temporal-spatial dynamics

Results show that the SPI and RDIst often have comparable trends and respond in a similar manner. Robust coefficients of determination (r^2) are obtained between both indices for the four reference time intervals (3 to 12 months) regarding all investigated meteorological stations. The r^2 ranged from 0.71 to 0.99. The corresponding means are 0.984, 0.901, 0.967 and 0.984 for 3, 6, 9 and 12 months, respectively. This suggests that both the SPI and RDIst provide largely similar results, and thus can be applied effectively to explore and analyse droughts for various time intervals.

Considering the 3-month, 6-month, 9-month and annual SPI (Figure 4-28 to Figure 4-31) and RDI (Figure 4-32 to Figure 4-35), and in particular the annual SPI and RDI, findings show that the basin suffered from the most significant drought events in 1999, 2000 and 2008. Results suggest that in 2008 both the annual SPI and RDI indicated that nearly the entire basin was under an extreme drought condition, while a small proportion experienced moderate drought patterns. In 2000, the annual SPI and RDI reported similar drought tendencies, where the upper and lower parts of the basin suffered from moderate droughts, while the remaining areas witnessed extreme drought conditions. For the SPI, the year 1999 had impressively similar drought patterns to the year 2000.

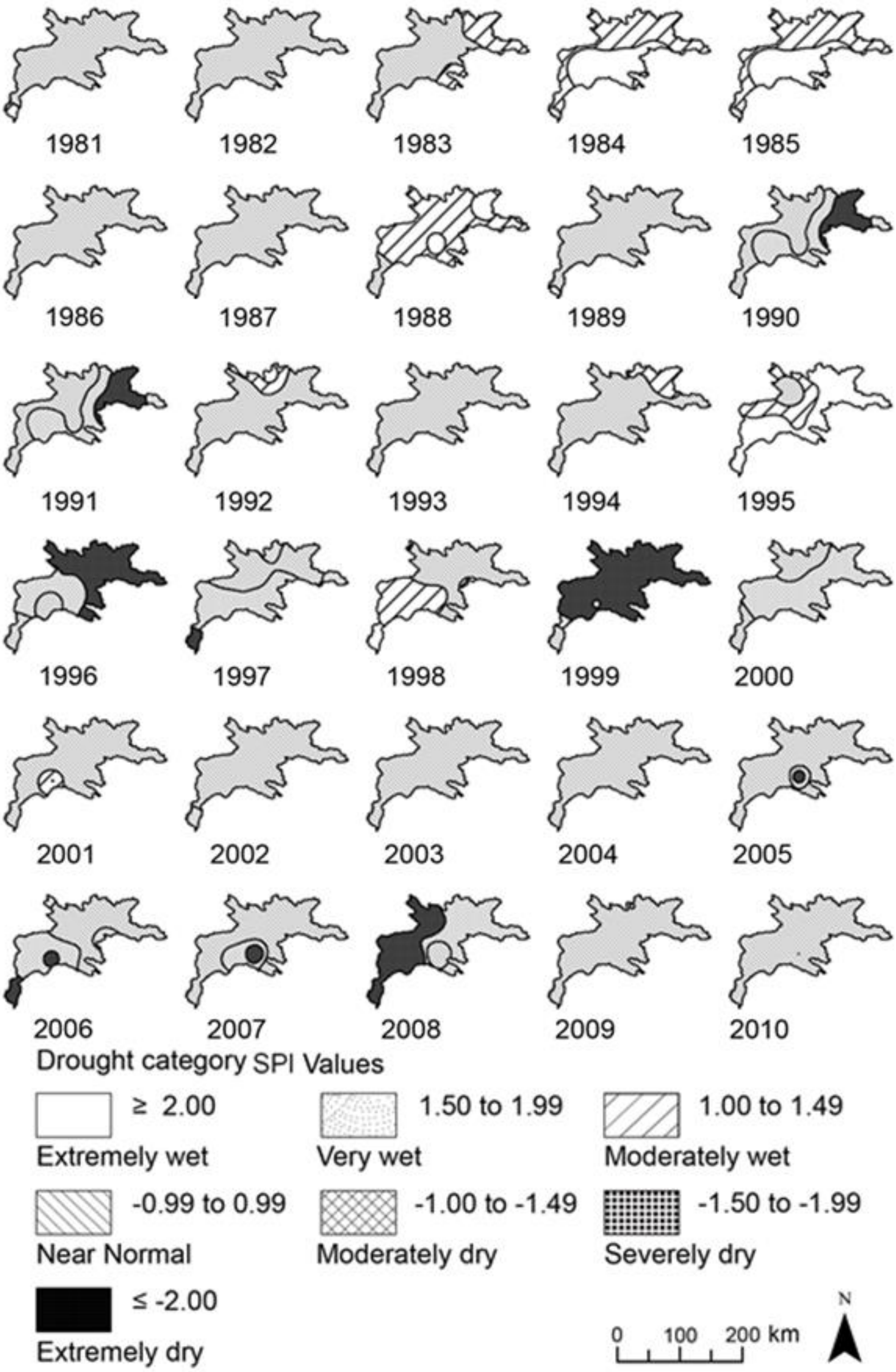

Figure 4-28: Three-month time interval temporal-spatial SPI dynamics between 1981 and 2010.

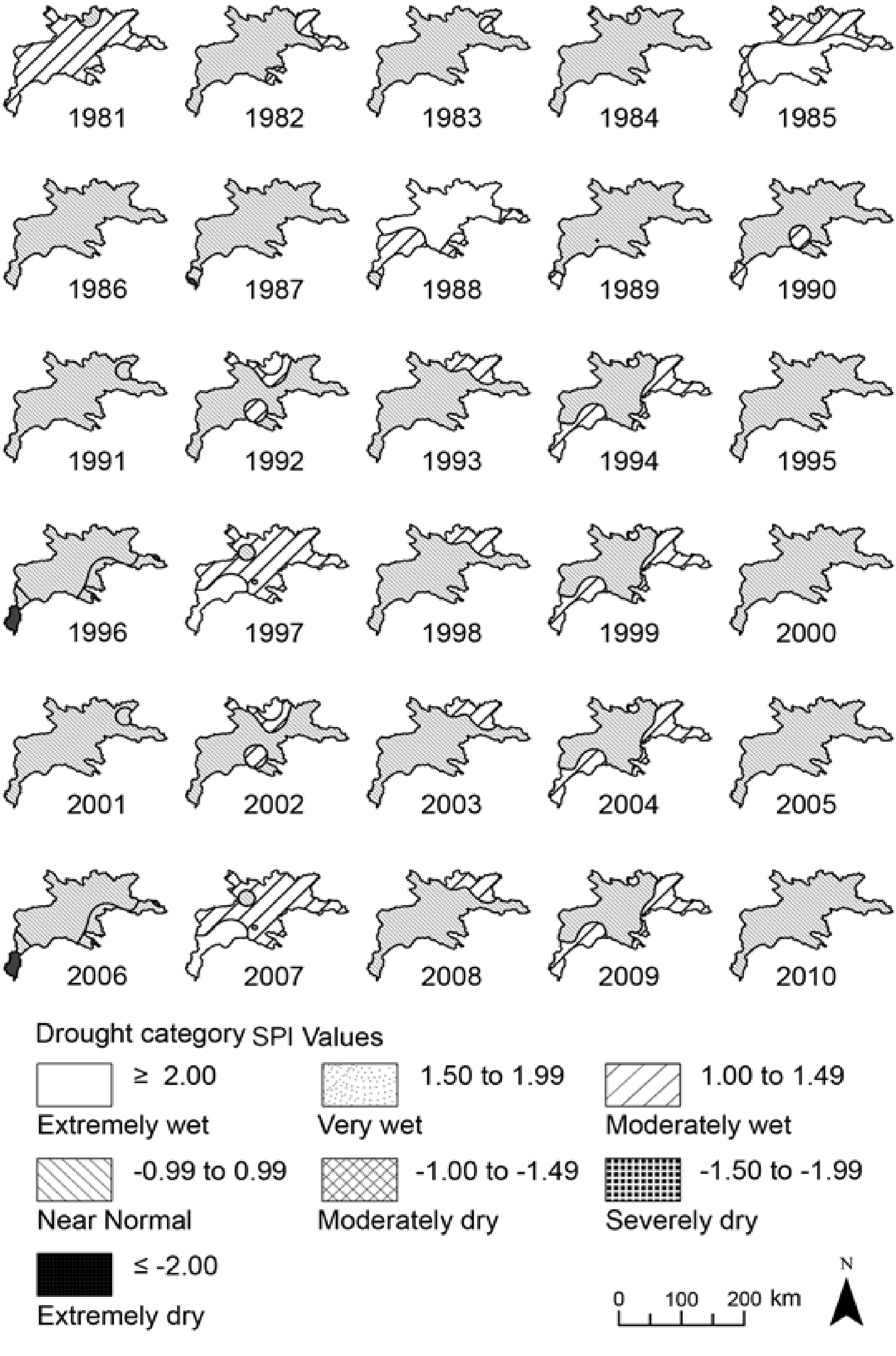

Figure 4-29: Six-month time interval temporal-spatial SPI dynamics between 1981 and 2010.

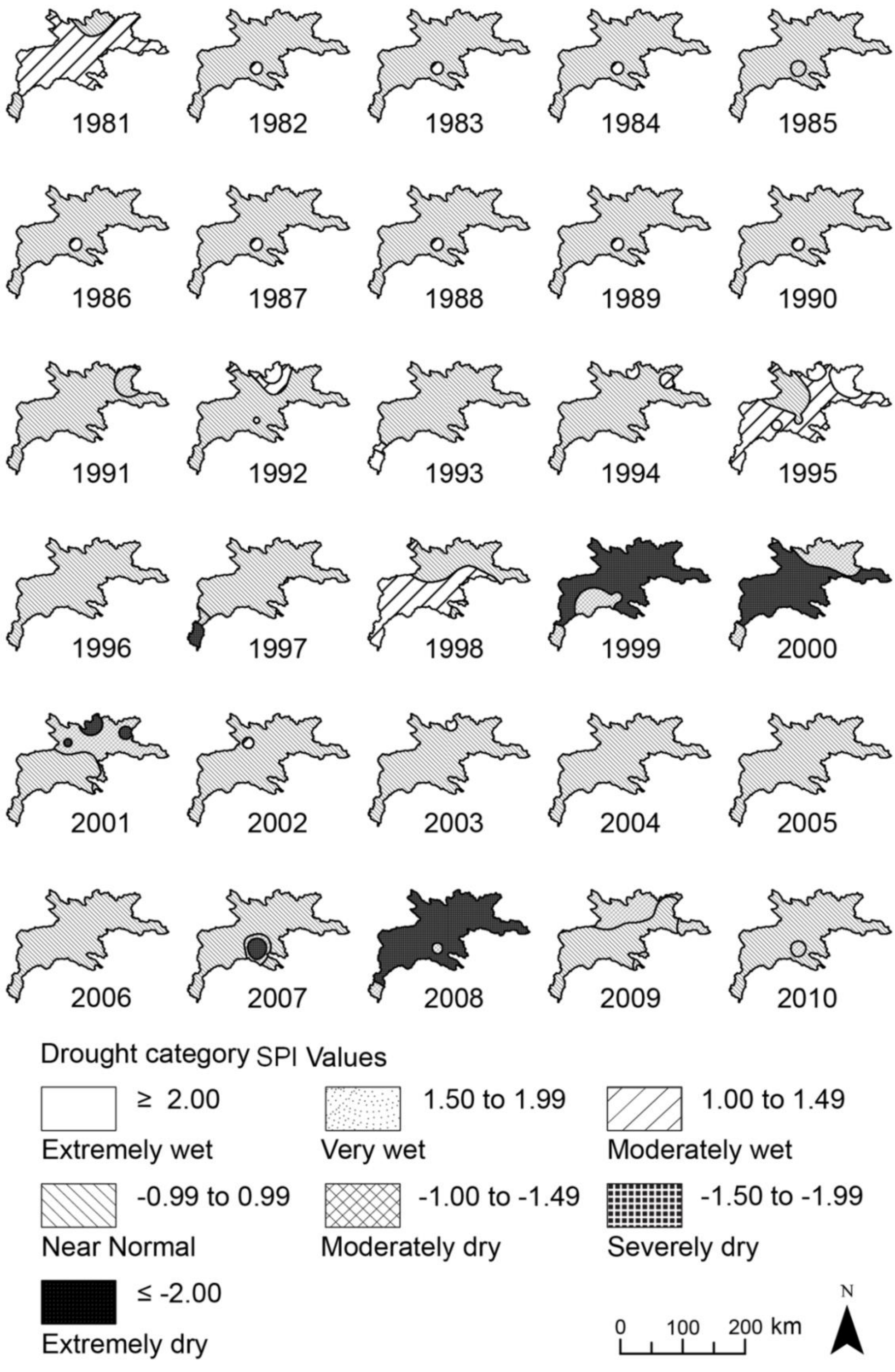

Figure 4-30: Nine-month time interval temporal-spatial SPI dynamics between 1981 and 2010.

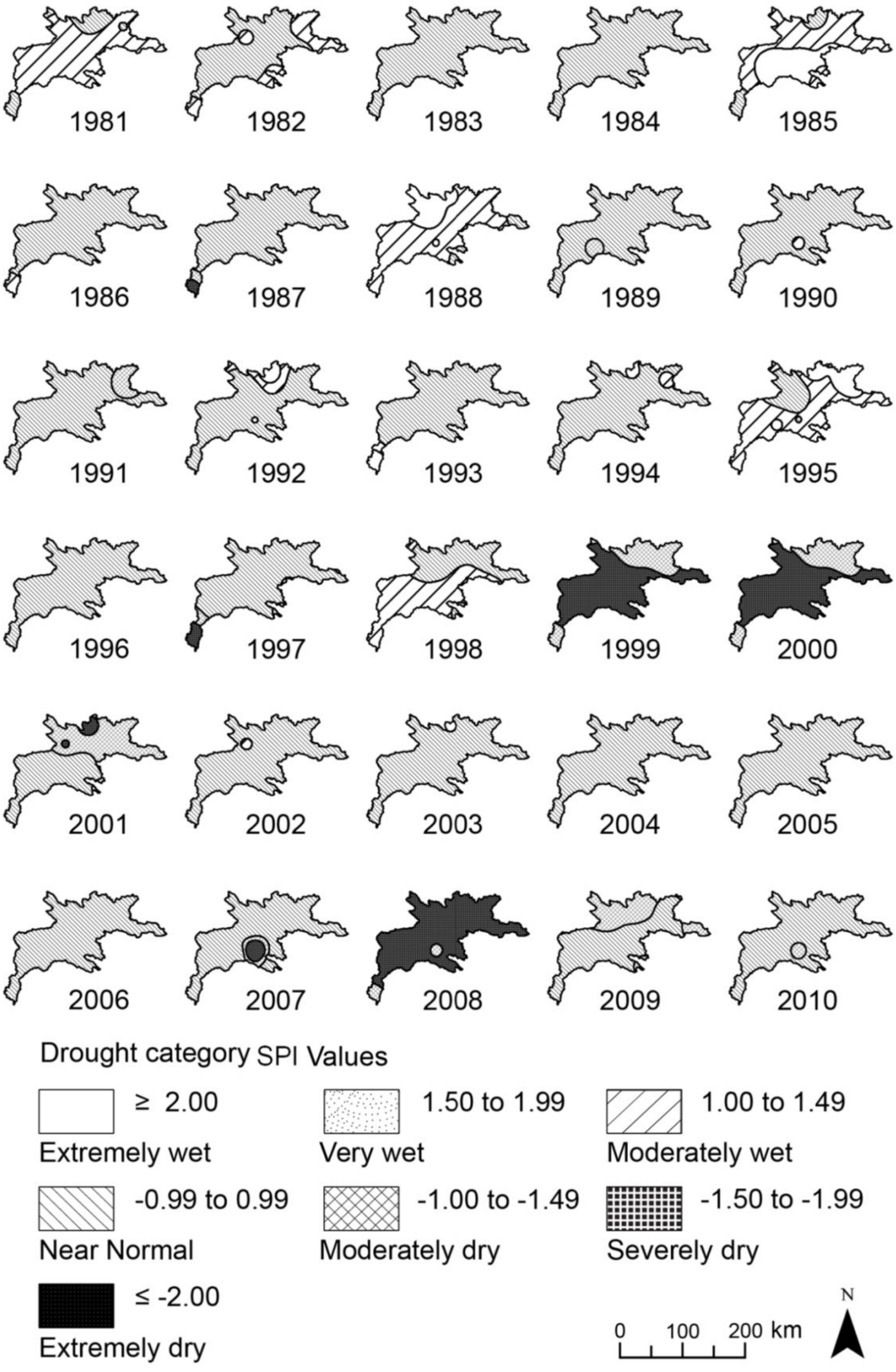

Figure 4-31: Annual temporal-spatial SPI dynamics between 1981 and 2010.

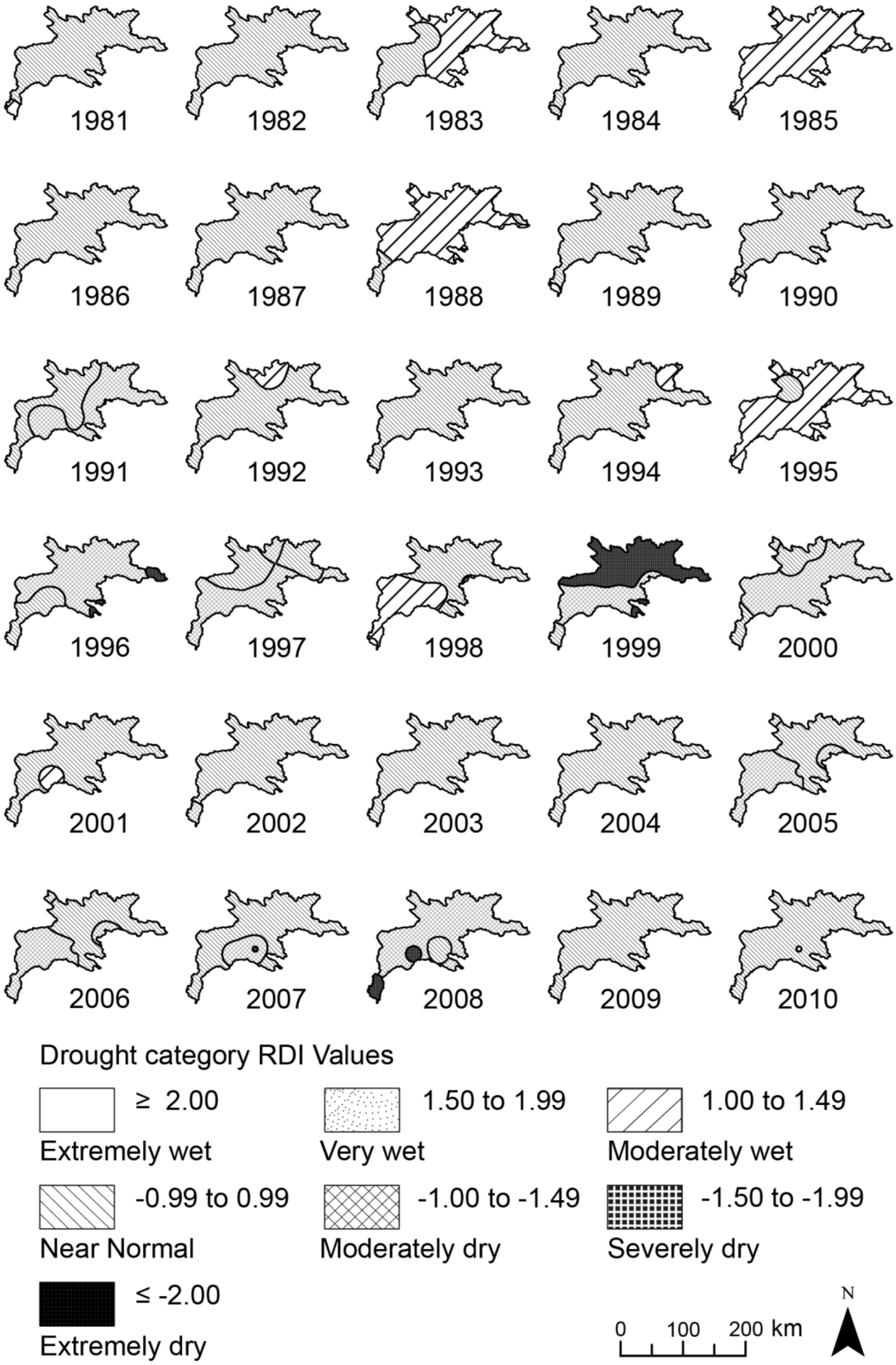

Figure 4-32: Three-month temporal-spatial RDI dynamics between 1981 and 2010.

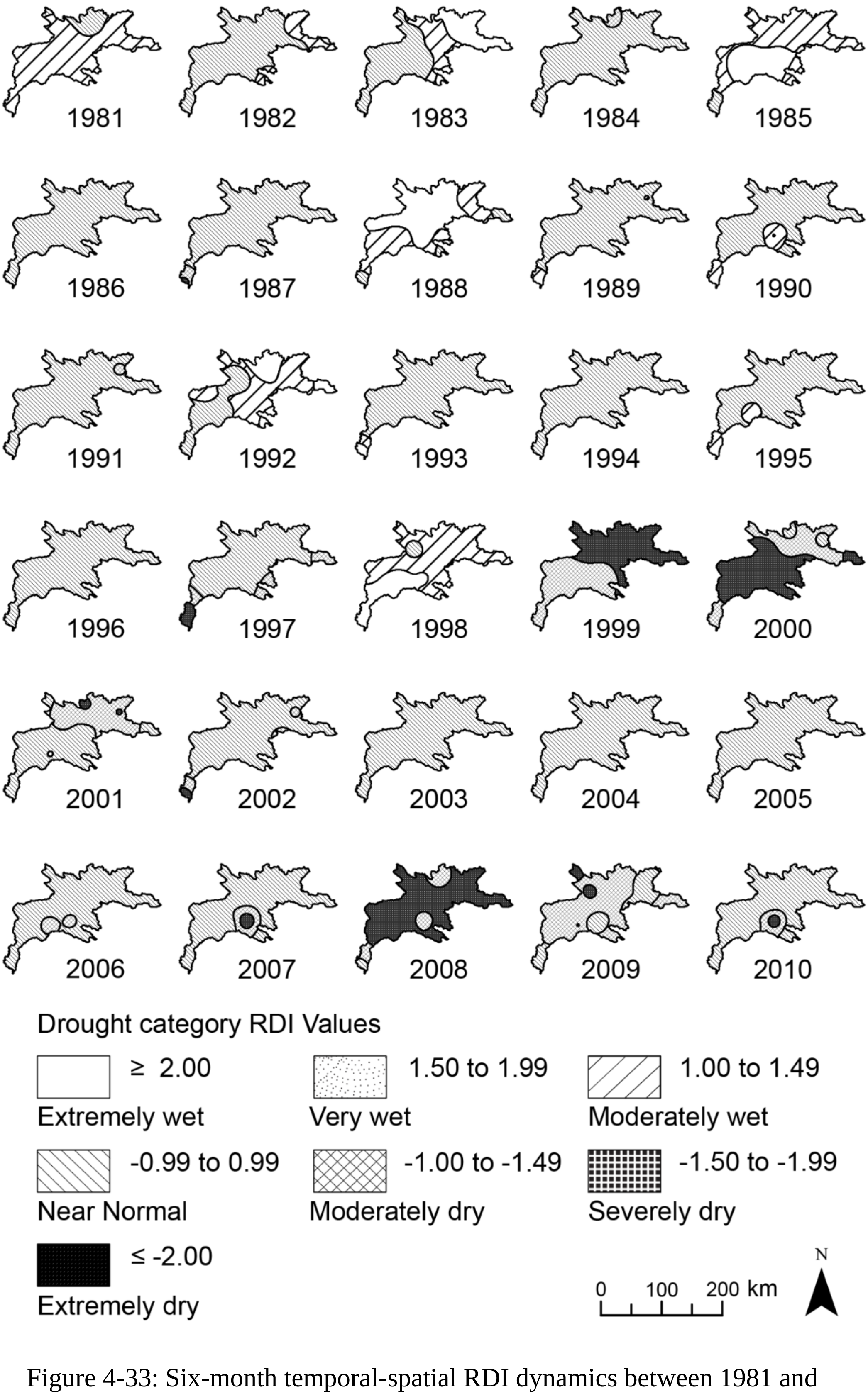

Figure 4-33: Six-month temporal-spatial RDI dynamics between 1981 and 2010.

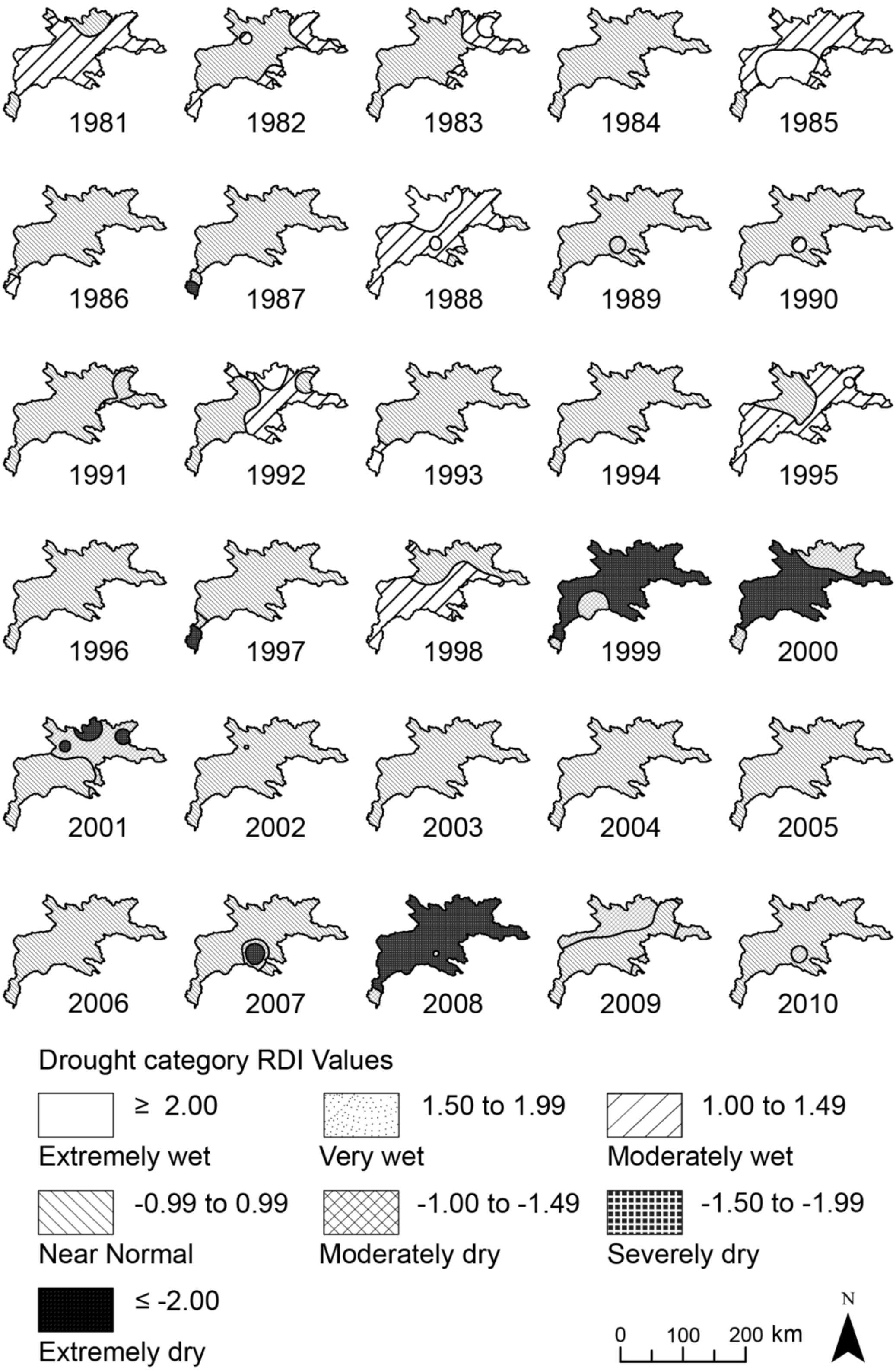

Figure 4-34: Nine-month temporal-spatial RDI dynamics between 1981 and 2010.

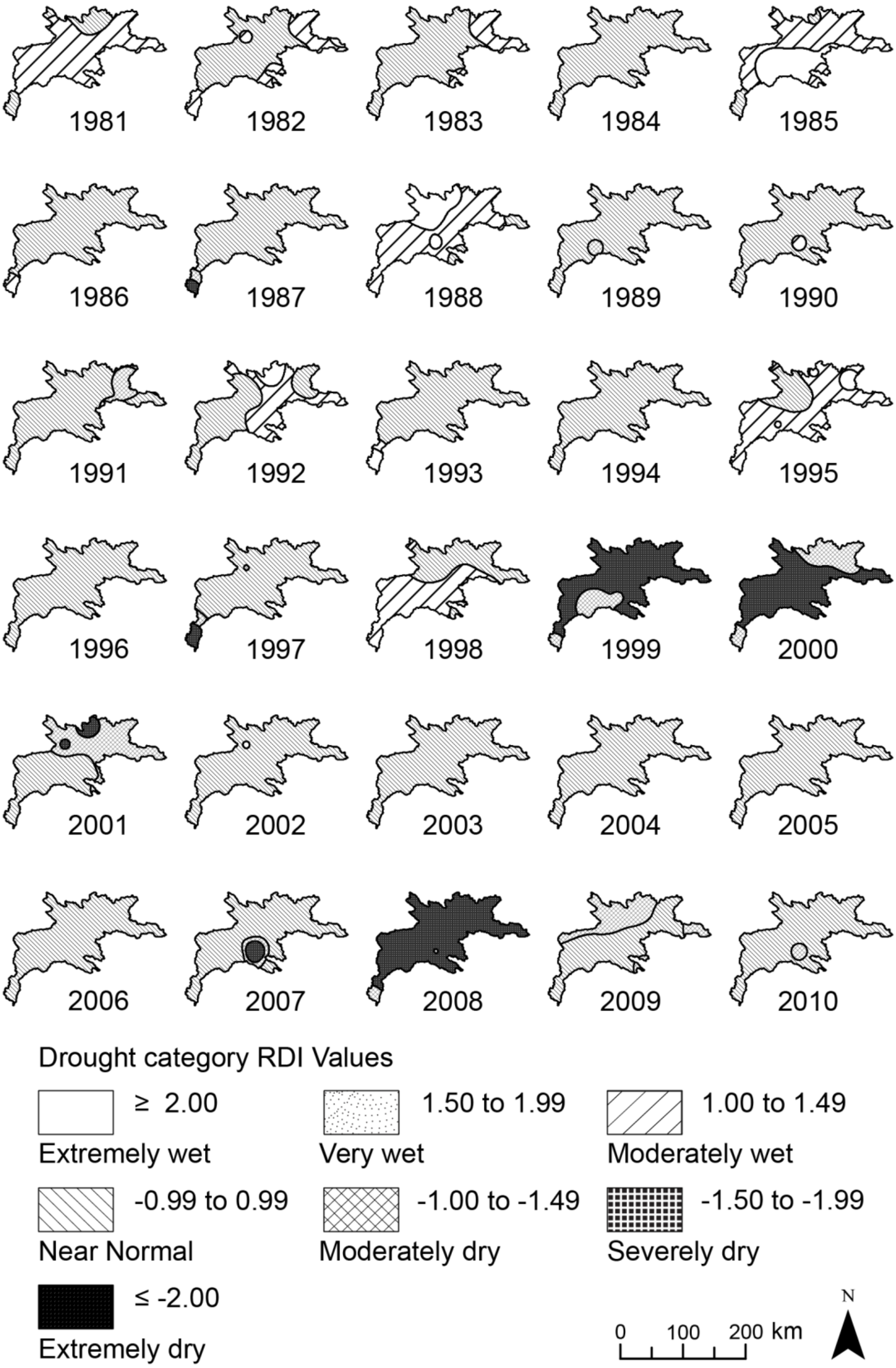

Figure 4-35: Annual temporal-spatial RDI dynamics between 1981 and 2010.

4.7.1 Importance of drought analysis and indices in supporting drought management

This section has been published in the following journal:

Al-Faraj F. A. M., Scholz M., Tigkas D., & Boni M. (2014e). Drought indices supporting drought management in transboundary watersheds subject to climate alterations. *Journal of Water Policy*. doi:10.2166/wp.2014.237

Analysis of historical droughts and use of drought indices support the development of water demand management and formulating action plans for various drought conditions. A system of priorities and trade-off of water use categories needs to be in place before droughts occur, so that each user knows, in advance of a drought, in what order water limitations will be applied. Correspondingly, a set of actions can be designed whereby a particular action can be put in place when a certain drought condition occurs.

The nation-wide plan is directed at providing water managers and other related stakeholders at various levels with effective and systematic means of assessing drought conditions, developing mitigation actions and programmes to reduce risk in advance of drought, and developing response options that minimize economic stress, environmental losses, and social hardships during drought. Furthermore, constraints to the planning process and to the activation of the plan in response to a developing drought will be identified. These constraints may be physical, financial, legal, or political. The costs associated with the development of a plan must be weighed against the losses that will likely result if no plan is in place. For the Diyala basin, the agriculture sector bears the most direct adverse impact of drought. Wells may run dry, crops may fail, and forage for livestock may be scarce.

Spatial and temporal drought analysis supports identification of high risk areas of the state and the most vulnerable economic and social sector. Moreover, a reliable assessment of water availability and its outlook for the short- and long-term is valuable information during dry periods. Drought indices assimilate a tremendous amount of data on precipitation, temperature, potential evapotranspiration, streamflow, water level, and other water supply indicators. The assessment of previous reactions in time and space to diverse drought conditions is a good planning aid, whereby weaknesses or problems caused or not covered can be distinguished and addressed. Drought analysis helps in establishing drought management zoning and regionalization, whereby the country can be divided into regions according to climatic characteristics, available water resources, socio-economic condition as well as other means such as vulnerability to drought.

4.8 Sensitivity of irrigation water requirements

The basin is agriculturally highly developed. The agriculture sector nowadays represents the largest water consumer of the developed water resources, in particular in the upper and middle parts of the basin in Iran, and in the lower portion in Iraq. An irrigation area of about 444,598 ha in Iraq and 130,498 ha of agriculture land in Iran are the total potential areas to be put under irrigation systems and developed on the entire basin. Moreover, the total fish farm area in Iran which is likely to be put into practice accounts for about 6010 ha.

The targeted net irrigation areas of the upper, middle and lower parts of the basin in Iraq are estimated at about 36,786 ha, 71,240 ha, and 336,572 ha, respectively, totalling about 444,598 ha (Table 3-2). The corresponding relative proportions to the total area were estimated at 8%, 16%, and 76%, respectively. The TIWR are estimated at 357.1 million m^3, 583.9 million m^3, and 3788.0 million m^3, respectively, totalling about 4.729 billion m^3 (Table 3-2). The corresponding relative proportions to the TIWR are estimated at 8%, 12%, and 80%, respectively. The total targeted net irrigation area of the upper and middle parts of the basin in Iran is estimated at some 81,918 ha and about 48,580 ha, respectively, totalling about 130,498 ha (Table 3-3). The corresponding relative proportions to the total irrigation area are estimated at about 63% and 37%, respectively. The TIWR are estimated at 852.6 million m^3 and 415.3 million m^3, respectively, totalling about 1267.9 million m^3. The total estimated water requirement for the fish farms is 143.4 million m^3.

Inefficient water conveyance schemes and on-farm irrigation arrangements, absence of withdrawals monitoring networks, deterioration of existing hydraulic infrastructures, and degradation and abandonment of some agriculture areas due to waterlogging and salinity are the main features of almost all existing irrigation projects in the lower riparian country. Decades of war, economic blockade and persistent security challenges delayed, to a large extent, the efforts to address the worsening problems in the agricultural sector.

Irrigation in both countries has a low efficiency on average. Major causes of inefficiency include: careless operation, poor maintenance, negligible water prices, fragmentation of responsibilities among different governmental agencies, and inadequate training of farmers. Introducing modern irrigation methods (e.g., low pressure pipe irrigation, pressurized sprinkler irrigation, and drip irrigation systems), minimizing water losses in the water conveyance networks, improving

ISP_{Eff}, and developing newly irrigated lands are the planned arrangements of almost all listed irrigation projects. The changes in TIWR according to a combined impact of incremental improvement in ISP_{Eff}, development in irrigation area and the use of the inter-basin water transfer system are shown in Table 4-21.

A close examination of the results of the first scenario at 40% ISP_{Eff} indicated that the anticipated annual shortage of water in the lower country will be about 589 million m^3 with no use of the existing inter-basin transfer system. If the transfer system is continually used at its current capacity, the corresponding yearly shortage of water will decline to approximately 302 million m^3, accounting for nearly 49% reduction. By improving the ISP_{Eff} by about 15% in both riparian states and with no compensation from the Tigris river, the lower country would annually save about 22 million m^3. If further improvement in the ISP_{Eff} is achieved such as 25% and 50% (the target), the corresponding annual water saving would be about 348 million m^3 and 972 million m^3, respectively. The yearly surplus volume of water could be allocated for further development such as to expand the irrigated areas.

Corresponding to the second scenario, results show clearly that with the 40% ISP_{Eff} (the current level), the potential additional annual amount of water needed to enable the lower country to achieve the targeted irrigation area accounts for nearly 2050 million m^3 and about 1761 million m^3, with no compensation and with the current compensation from the Tigris river, respectively. When the inter-basin water transfer system is not in use, the targeted irrigation area of the downstream state cannot be achieved even if the ISP_{Eff} in both countries soared to 60%, accounting for improvement of 50%. Findings also show that the targeted irrigation area of the downstream party can only be put in place, when the ISP_{Eff} climbs to 58% in both states, accounting for improvement of 45% and with annual compensation from the Tigris river estimated at about 143 million m^3.

The third, fourth and fifth scenarios show a set of possible proportions of compensation (i.e. inter-basin water transfer system) from the Lesser Zab river in Iraq. As far as scenario 3 is concerned, the lower actor can develop the targeted irrigation area with 15% improvement in the ISP_{Eff} in both countries and annual contribution from Lesser Zab and Tigris rivers of about 1248 million m^3. When further development in the ISP_{Eff} is achieved and with continued support of the inter-basin transfers systems, higher stages of water saving can be reached.

Results also indicate that the level of ISP_{Eff} that both states can achieve, and the proportional compensation of the two inter-basin transfer systems, would identify the additional area, which can be put under an irrigation system and the annual amount of water that would be saved. Figure 4-36 illustrates the deficit/surplus of water based on incremental improvement in irrigation system performance efficiency.

The overall findings are in good agreement with what was pointed out by Seckler, Barker, and Amarasinghe (1999), that increasing irrigation effectiveness from 43% to 70% worldwide would produce a total annual water saving of approximately 944 billion m^3 and reduce the need for development of further water supplies for all sectors in 2025 by nearly 50%.

Table 4-21: Sensitivity of total irrigation water requirements to incremental development in irrigation system performance efficiency and capacity of potential available inter-basin water transfer schemes (Table 4-21 continuous on next page).

ISP_{Eff} (%)	% change in ISP_{Eff}	Annual flow (million m^3)		Water allocated (million m^3)	Difference (million m^3)	Annual flow (million m^3)	
		Consumption in Iran	Left to Iraq			Inter-basin transfer	Shortage/ surplus
Scenario 1							
40	0	2789.3	2680.7	3269.6	-588.9	287.6	-301.3
42	5	2722.1	2747.9	3113.9	-365.9	287.6	-78.3
44	10	2661.0	2809.0	2972.3	-163.3	287.6	124.3
46	15	2605.2	2864.8	2843.1	21.7	287.6	309.3
48	20	2554.1	2915.9	2724.6	191.3	287.6	478.9
50	25	2507.0	2963.0	2615.6	347.3	287.6	634.9
52	30	2463.6	3006.4	2515.0	491.4	287.6	779.0
54	35	2423.4	3046.6	2421.9	624.7	287.6	912.3
56	40	2386.0	3084.0	2335.4	748.6	287.6	1036.2
58	45	2351.3	3118.7	2254.9	863.8	287.6	1151.4
60	50	2318.8	3151.2	2179.7	971.4	287.6	1259.0
Scenario 2							
40	0	2789.3	2680.7	4729.0	-2048.3	287.6	-1760.7
42	5	2722.1	2747.9	4503.8	-1755.8	287.6	-1468.2
44	10	2661.0	2809.0	4299.0	-1490.0	287.6	-1202.4
46	15	2605.2	2864.8	4112.1	-1247.3	287.6	-959.7
48	20	2554.1	2915.9	3940.8	-1024.8	287.6	-737.2
50	25	2507.0	2963.0	3783.2	-820.2	287.6	-532.6
52	30	2463.6	3006.4	3637.7	-631.2	287.6	-343.6
54	35	2423.4	3046.6	3502.9	-456.3	287.6	-168.7
56	40	2386.0	3084.0	3377.8	-293.9	287.6	-6.3
58	45	2351.3	3118.7	3261.3	-142.6	287.6	145.0
60	50	2318.8	3151.2	3152.6	-1.5	287.6	286.1

ISP_{Eff} (%)	% change in ISP_{Eff}	Annual flow (million m^3)		Water allocated (million m^3)	Difference (million m^3)	Annual flow (million m^3)	
		Consumption in Iran	Left to Iraq			Inter-basin transfer	Shortage/ surplus
Scenario 3							
40	0	2789.3	2680.7	4729.0	-2048.3	1233	-815.3
42	5	2722.1	2747.9	4503.8	-1755.8	1233	-522.8
44	10	2661.0	2809.0	4299.0	-1490.0	1233	-257.0
46	15	2605.2	2864.8	4112.1	-1247.3	1233	-14.3
48	20	2554.1	2915.9	3940.8	-1024.8	1233	208.2
50	25	2507.0	2963.0	3783.2	-820.2	1233	412.8
52	30	2463.6	3006.4	3637.7	-631.2	1233	601.8
54	35	2423.4	3046.6	3502.9	-456.3	1233	776.7
56	40	2386.0	3084.0	3377.8	-293.9	1233	939.1
58	45	2351.3	3118.7	3261.3	-142.6	1233	1090.4
60	50	2318.8	3151.2	3152.6	-1.5	1233	1231.5
Scenario 4							
40	0	2789.3	2680.7	4729.0	-2048.3	945.4	-1102.9
42	5	2722.1	2747.9	4503.8	-1755.8	945.4	-810.4
44	10	2661.0	2809.0	4299.0	-1490.0	945.4	-544.6
46	15	2605.2	2864.8	4112.1	-1247.3	945.4	-301.9
48	20	2554.1	2915.9	3940.8	-1024.8	945.4	-79.4
50	25	2507.0	2963.0	3783.2	-820.2	945.4	125.2
52	30	2463.6	3006.4	3637.7	-631.2	945.4	314.2
54	35	2423.4	3046.6	3502.9	-456.3	945.4	489.1
56	40	2386.0	3084.0	3377.8	-293.9	945.4	651.5
58	45	2351.3	3118.7	3261.3	-142.6	945.4	802.8
60	50	2318.8	3151.2	3152.6	-1.5	945.4	943.9

ISP_{Eff} (%)	% change in ISP_{Eff}	Annual flow (million m^3)		Water allocated (million m^3)	Difference (million m^3)	Annual flow (million m^3)	
		Consumption in Iran	Left to Iraq			Inter-basin transfer	Shortage/ surplus
Scenario 5							
40	0	2789.3	2680.7	4729.0	-2048.3	472.7	-1575.6
42	5	2722.1	2747.9	4503.8	-1755.8	472.7	-1283.1
44	10	2661.0	2809.0	4299.0	-1490.0	472.7	-1017.3
46	15	2605.2	2864.8	4112.1	-1247.3	472.7	-774.6
48	20	2554.1	2915.9	3940.8	-1024.8	472.7	-552.1
50	25	2507.0	2963.0	3783.2	-820.2	472.7	-347.5
52	30	2463.6	3006.4	3637.7	-631.2	472.7	-158.5
54	35	2423.4	3046.6	3502.9	-456.3	472.7	16.4
56	40	2386.0	3084.0	3377.8	-293.9	472.7	178.8
58	45	2351.3	3118.7	3261.3	-142.6	472.7	330.1
60	50	2318.8	3151.2	3152.6	-1.5	472.7	471.2

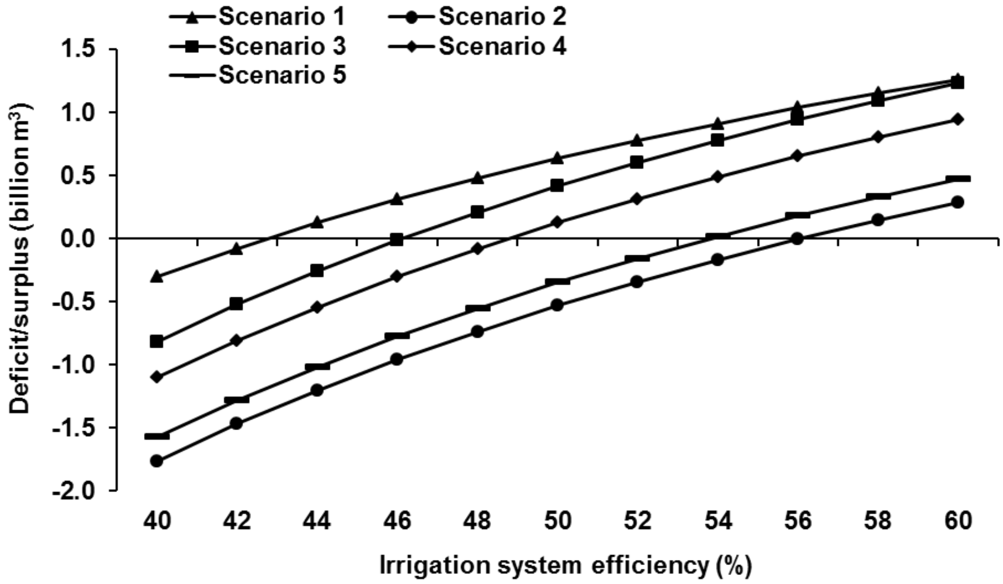

Figure 4-36: Deficit/surplus based on incremental improvement in irrigation system performance efficiency and capacity of potential available inter-basin water transfer schemes.

4.9 Adaptation and mitigation measures

4.9.1 Mitigation options to climate change in water sector

The potential mitigation measures to climate change in the water sector are schematized in Figure 4-37 (*After* Al-Faraj & Scholz, 2014b). The diagram suggests that the potential options can be mainly placed in two categories: (1) the supply-side, and (2) the demand-side.

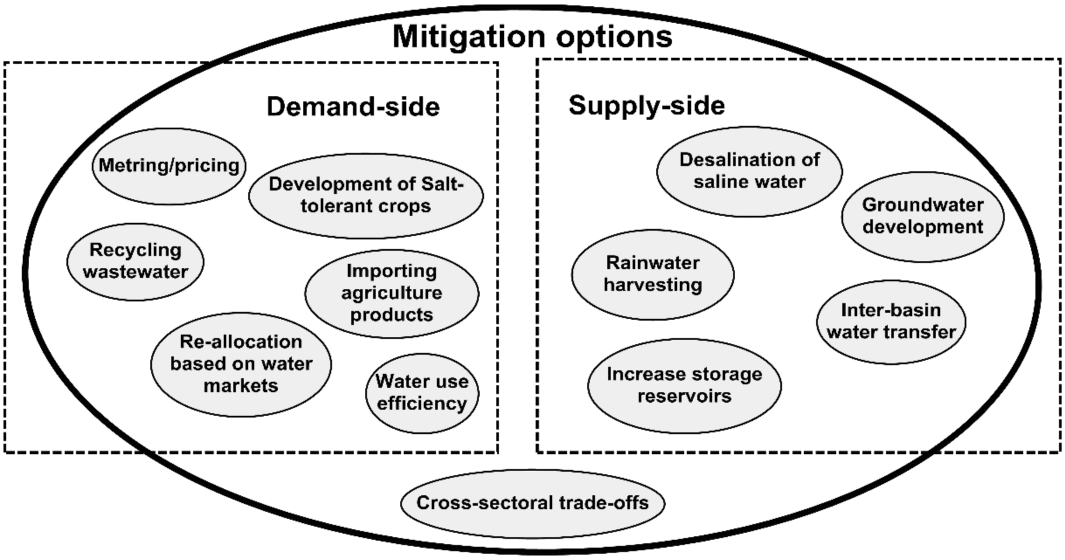

Figure 4-37: Mitigation options interaction with supply-side and demand-side in water sector (*After* Al-Faraj & Scholz, 2014b).

Climate change is a long-term process of incremental change, yet increased temperature, potential evapotranspiration and frequency of droughts, have become major concerns for most arid and semi-arid climate countries due to their long-term economic and social implications and potential adverse effects on the everyday lives of people. The collective impact of basin-wide climate change and upstream human-induced perturbations involves complex interactions between climatic, environmental, economic, political, institutional, social, and technological processes. Incorporating and mainstreaming adaptation to and attenuation of the joint potential adverse impact into the core short- to long-term water governance plans and policies at national scale, sub-national level and basin-wide context is a crucial strategy for sustainable development of the transboundary water resources.

4.9.2 Technical framework

The success of adaptation and mitigation measures to handle potential collective impacts requires addressing risks in a changing climate and non-climatic drivers. In most developing countries, a remarkable deficit exists in terms of adaptive capacity, which makes communities extremely vulnerable to cope with potential combined risks. Flexible adaptation measures to manage current and anticipated future effects, are urgently needed to lessen the current adverse impacts and to increase resilience against the likely future influences.

The proposed technical framework (Figure 4-38) can support the sustainable management of transboundary river basins of scarce waters, under the combined effect of upstream human-pressure and climate change at basin level. The framework helps make appropriate decisions in six main domains. These domains are: (1) Cross-sectoral trade-offs; (2) Improve water use efficiency; (3) Inter and intra-basin water transfer systems; (4) Cutbacks in demand/maintaining environmental flow in the river; (5) Developing a sound groundwater planning policy; and (6) Quantify current supply-demand gaps and sizing a future gap.

However, to achieve a sustainable management of transboundary water bodies, the support of the United Nations and the international agencies such as the UNDP, UNESCO, USAID, USGS, FAO and the World Bank is crucial for initial diagnosis of the knowledge gaps and to launch a multi-level and interdisciplinary long-term capacity building programme.

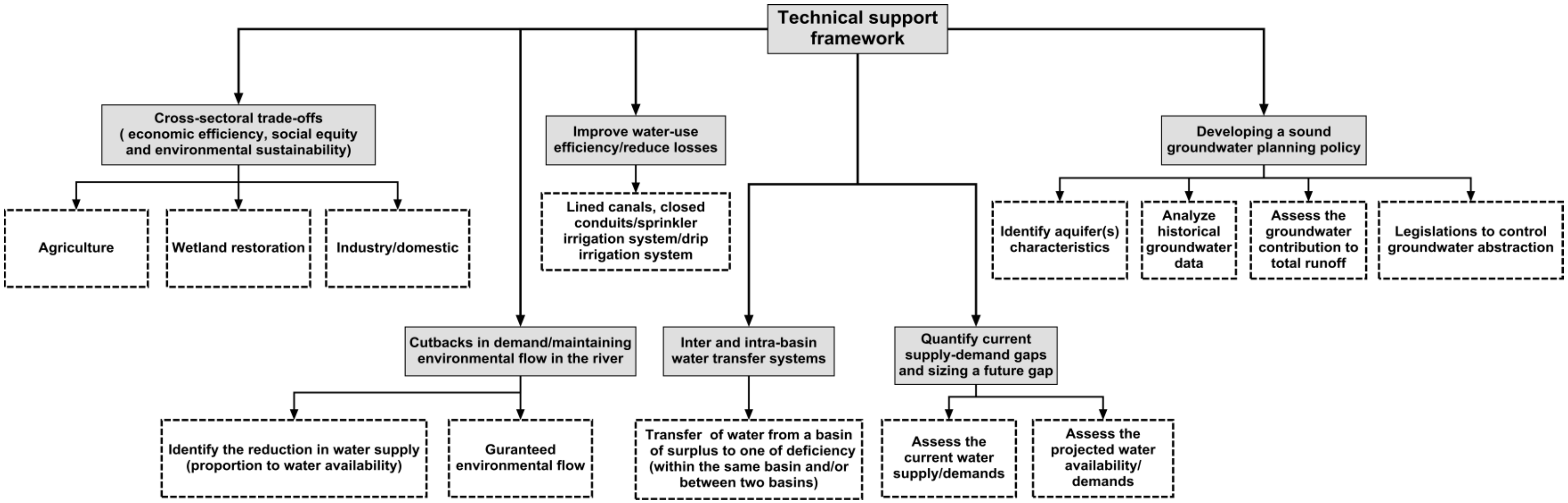

Figure 4-38: Technical framework supporting decision-making

A key component of an effective capacity-building programme and knowledge management is an explicit identification of the capacity gaps, constraints and challenges, identification of the institutional strengthening and human-resources development needs, and preparation of a prioritized list of fragile sectors that urgently need a capacity building programme to manage collective adaptation and mitigation efforts. Figure 4-39 illustrates the training process that could be useful to follow and assess the training lessons.

The training programme requires a sustained, long-term obligation to empower workforce and partners by providing technical guidance materials, dissemination of pilot project research findings and relevant research products, and tools necessary to move from knowledge to appropriate action. However, among the reasons for the partial failure of the training programmes are:

a. Lack of clear post training follow up plans: trainees often returns to their departments without a clear plan on how to make use of what they have learned, on their daily work. As a consequence, in a short period of time, lessons learned will be forgotten.
b. Lack of institutional support to allow the right trainees to complete training programs: often, trainers that have participated to one training session are not allowed to participate to a follow up program and, as a result, for some advance technologies it is not possible to complete training programs successfully.
c. Lack of linkages between university and industry: trainees are often chosen only among ministerial offices thus failing to recognize the

importance that university students might play as future governments' employees.

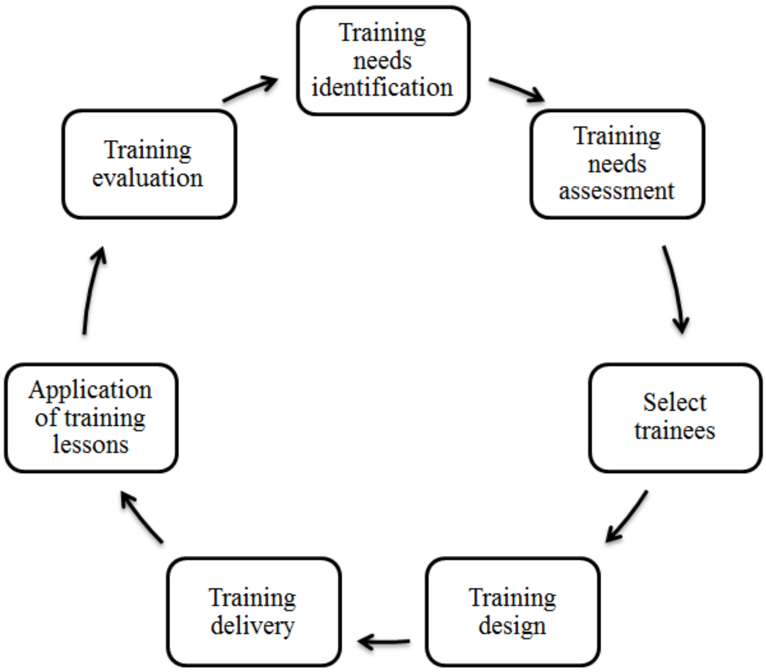

Figure 4-39: Training process

Efficient measurable goals and performance metrics should be covered in the capacity-building training programme to continuously assess whether adaptive actions are achieving desired outcomes. Adaptation strategies and actions will likely lack the required support for active implementation, without effective outreach efforts to bring the collective impact and consequences to the public, tribals, private sector and non-governmental organizations.

Concerning the policy and legal frameworks, the first critical step is to assess whether the current federal level is capable of handling the current situation and hence is adaptable to the challenges ahead.

A constraining factor is the lack of accurate, reliable and up-to-date data. A lack of localized climate data causes a gap in understanding climate impact and vulnerabilities, making it difficult for nation and river basin-based response strategies, to be developed.

The acquisition of real-time hydro-meteorological data is a critical and key component for nation-based water resources management and for developing a basin-wide water balance plan and strategy (Zubari, 2002). Transparent exchange of information and collective gathering of data are essential to develop the joint knowledge base needed to handle and cope with the mutual effect and better assess the proximate and root causes of vulnerabilities. Analysis of past extreme events and trends contributes to the determination of the climate change threats. O'Donnell, Ewen, and O'Connell (2011) have pointed out the importance of considering the historical extreme rainfall events in formulating mitigation programmes, especially when such events are likely to become more frequent in the future.

Transparency in disseminating data and exchange information between stakeholders, particularly during extreme events is a crucial element. Sharing of information at multi-governmental levels, with non-governmental organizations (NGOs), private sector, tribal communities, and professional associations and making the information more accessible and easier to understand is a key to achievement of operative adaptation and mitigation measures. Adaptation requires facilitating better coordination and strong partnerships across multiple agencies, sectors and scales, suggesting the need for collective action.

Assessment of potential key vulnerabilities is intended to provide information on rates and levels of potential negative impacts to help decision makers make appropriate responses to the risks of mutual impact. Developing a set of maps for hotspot areas is another decisive component in the adaptation and mitigation process. Communities, areas, sectors and infrastructure that are at high risk and have a low capacity to respond should be spatially mapped. Recent findings from the lower Mekong and Dniester river basins case studies (Corobov et al., 2013; USAID, 2013) have pointed out that identification of the hotspot areas enables the analysis to be focused on areas likely to be most affected by future changes in climate. Adaptation and mitigation planning and management should apply risk-management and ecosystem-based approaches, where relevant, to help identify, assess and prioritize options to reduce vulnerability and increase ecosystem resilience to potential environmental, social and economic implications of the mutual impact.

Vulnerability assessments and adaptation strategy development and implementation require scientific, technical, planning, financial, and coordination capacity, which many countries cannot provide. Furthermore, many countries must direct time and resources into dealing with more immediate development challenges and defer considering adaptation actions. This challenge can begin to be addressed through giving government officials and civil society increased capacity to mainstream climate change into sectoral plans and incorporate it into the mandate and capabilities of relevant national and local authorities.

Integrated water-land management practices include rain water harvesting systems. The importance of rain water harvesting for various agricultural activities has received great attention, particularly in arid and semi-arid regions (Senkondo et al., 2004; Mati, Malesu, & Oduor, 2005; Sonbol, 2006). Moreover, the rain water harvesting has been increasingly considered as an adaptation measure to climate change (Pandey, Gupta, & Anderson, 2003; EA, 2009; Singh & Kandar, 2012). The use of managed aquifer storage to augment ground water resources through setting up artificial aquifer recharge systems such as man-made infiltration basins and injection wells is among committed adaptation arrangements. Assessing the aquifers' storage bearing capacities and defining the period in which optimal water withdrawal can be achieved are of paramount importance in the integrated water resources management.

Other encouraging arrangements, such as the natural buffers like the wetlands, can play an important role in storing the water in the wet season and feeding the rivers in the dry periods via regulatory structures and conveying schemes. The inter-basin water transfer system (IBWTS) is a potential management practice to transfer water from the 'donor' basin to the river basin referred to as the 'receiving' basin to meet growing residential, commercial, agricultural, industrial, hydropower, recreation and fish farms demands. Managing water use in agriculture is one of the key themes relating to water scarcity and drought. Improvement of ISP_{Eff} and efficient recycling of irrigation return flow can be considered among possible actions to efficiently use the water resources in water limited environments.

Land use reform and private sector engagements are further promising practices; for instance dividing the government collective farms into small holding farm associations fully run by the private sector or jointly with local government authorities. Another example is to shift from a supply-side approach to a more conservative 'demand-side' solution associated with benefit-cost analysis to avoid over-exploitation of limited water resources. The UNECE (2011a) has reported that to adapt to climate change, a mixture of structural and non-structural adaptation measures is needed. Structural measures such as dams, dykes and flood forecasting systems are necessary, but non-structural measures such as water use reduction or water use efficiency, increasing ecosystem resilience and land use reform can be highly effective.

Domestic and irrigation metering and economic water pricing create consistent obligation and incentives for consumers to use water more efficiently and is a pre-condition for suitable application of a tariffs policy (Zubari, 2002). Applying a water market-based water allocation mechanism can achieve a more efficient and economic water allocation. Water Banks are a special form of water markets, and can be seen as a framework or design option for the trade of water use rights. Conducting baseline-collective impact assessment studies can enable the hotspot areas, resilience and adaptive capacity to be defined.

However, to assure that adaptation and mitigation measures remain effective in the long run, it is crucial to elaborate a long-term operations and maintenance strategy as well as spell out a concrete action plan for each measure.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 Introduction

This thesis reports upon a set of novel methods and approaches for analyzing the impacts of both climate change/variability and upstream human impacts on downstream flow regime within a transboundary river basin, and on specific interventions that could adapt to/mitigate the resulting impacts.

This chapter demonstrates how the objectives of this research were achieved and how these objectives were integrated together to deliver the aim: a coherent technical framework that can support the decision-making to sustainably manage the transboundary river basins of scarce water resources. The framework encompasses of six main themes: These themes are: (1) cross-sectoral trade-offs; (2) improve water-use efficiency/reduce water losses; (3) developing a sound groundwater planning policy; (4) cutbacks in demand/maintaining environmental flow in the river; (5) inter and intra-basin water transfer systems; and (6) quantify current supply-demand gaps and sizing a future gaps.

5.1.2 Achievement of the Research Aim and Objectives

The overall aim of the thesis was to develop a coherent technical framework that can support the management of transboundary river basins in a sustainable manner, under the mutual impact of upstream human-interventions and climate change at basin scale, particularly in arid and semi-arid areas. To achieve this aim, four objectives were developed, which were fully achieved. The findings associated with each objective are discussed throughout this thesis and are noted below:

Objective 1: To identify and separate the impacts of historical droughts and upstream development on the lower basin flow regime. Estimation of groundwater contribution to total unimpaired runoff.

Upstream development has considerably changed the lower basin flow regime. The alteration in flow paradigm is anticipated to increase when the key hydraulic works such as the Nosoud inter-basin water transfer scheme and the Darian dam (currently both under construction) will be commissioned and subsequently operated in 2018. Future anticipated frequent drought spells and upstream development represent a dual threat to the lower basin flow demand. Three simple empirical generic formulas, which form part of the technical support framework, are developed for estimating the artificially, climatically and collectively impaired mean annual flow volumes available to a downstream country.

Another supportive tool within the technical framework is that the study is successfully integrated the flow duration curve method with two one-parameter digital filtering algorithms to deliver a generic approach for obtaining the optimal value for the filter parameter (α) and reasonably compute the temporal changes of the base flow contribution to the total lower basin flow. The approach has overcome the shortcomings suffered by the digital filtering algorithms. The proposed method helps to identify the impact of upstream anthropogenic river regulation, water abstraction and landscape modifications on the natural release of groundwater reserves to the downstream river system, particularly during dry periods.

A generic statistical tool is also developed, as part of the technical support framework, to separate the relative effect of upstream development from the combined impacts. The proposed method supports water managers in unbiased, timely and spatially relevant decision-making processes.

Objective 2: To assess the possible impacts of climate change/future development at the basin level on the lower basin flow paradigm.

As an integral part of the technical support framework, a simple, generic, powerful and novel approach is presented for predicting the proportional change (%) in the mean annual runoff under various climate change scenarios and anticipated droughts. The proposed methodology offers a solid tool to support water managers and decision-makers in shaping better management plans and strategies for water resources that are anticipated to be available in the short to long term.

Objective 3: To assess the sensitivity of irrigation water requirements to a spectrum of improvements in irrigation efficiency at basin scale and lower basin's inter-basin water transfer schemes.

Findings suggest that even with increasing irrigation efficiency from 40% to 60% and the use of inter-basin water transfer systems from two donors, these measures would not be enough to completely handle the potential impact of climate change. This entails a serious and deep review of historical plans on expanding the agricultural areas and put into effect urgent actions and workable adaptation measures such as water harvesting systems. A shift from the traditional irrigation approach (e.g. gravity irrigation) to modern techniques (e.g. drip and sprinkler irrigation) and improved conveyance efficiency would reduce irrigation demands, but in return, it will be more expensive and requires experience and continuous maintenance.

Objective 4: Integrate methods into a durable technical framework that can support decision-making for mitigation to and adaptation with the collective impact. The novel tools and approaches, which were successfully developed in this thesis, are casted to form a solid framework that can technically support the sustainable management of transboundary basins of scarce water resources.

5.1.3 The Contribution to Knowledge

The thesis delivered a firm technical framework (Figure 4-38) that can sustenance the sustainable management of transboundary river of scarce water resources. Findings will support water managers to override managing the unit of the basin, which lies within the country territory to a more proper and wider scale of management referring to the transboundary level. Moreover, it will support decision makers in making better decisions timely and spatially that strengthen resilience, in particular the lower riparian country, to handle and cope with the potential combined effect of climate change and upstream development.

A set of eight papers abstracted from the thesis, five of which have already been published in peer-reviewed journals, while the other three are in review. This suggests an impressive contribution to the knowledge and represents a method through which the contribution was disseminated.

5.1.4 The Main Conclusions

The thesis has successfully develop a sound framework that can technically assist the decision makers through a set of tools, which can be used for analyzing the collective impact of climate change and upstream man-made activity on lower basin flow paradigm. Moreover, through a set of measures, which can be adopted to adapt to/mitigate the potential resulting impacts.

5.1.5 Recommendations for Future Improvements

Three main recommendations are listed below to be considered for further research work.

1. Perform analysis at some hotspot areas to assess socio-economic vulnerability for appropriate identification of how adaptation investments can most effectively boost the resilience level of communities in response to the collective adverse influence of climate change at the river-basin level and upstream human-induced interventions.
2. Perform analysis to assess the effectiveness of some of the adaptation practices and mitigation measures, such as rainwater harvesting systems, improvement of irrigation efficiency, optimizing storage reservoirs and inter-basin water transfer systems. This can be conducted at some existing pilot projects.
3. Perform drought forecasting analyses and studies of high reliability at transboundary basin-wide scale, particularly in arid and semi-arid regions, taking into account potential spectrum of uncertainties. This could benefit from the developments in global drought monitoring and forecasting.

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APPENDICES

Appendix 1 Request for data - MoAgWR-KRG-Directorate of Dams and Reservoirs

University of Salford MANCHESTER

School/Department: Civil Engineering
College: College of Science and Technology
Contact details: Dr. Devi Prasad Tumula, Senior Lecturer, Civil Engineering Directorate.

Web address: http://www.salford.ac.uk

Date: 11/03/2013

To Whom It May Concern

To,

Ministry of Agriculture and Water Resources - KRG - General Directorate of Dams and Reservoirs
Ministry of Agriculture and Water Resources - KRG- Derbendikhan Dam Directorate
Ministry of Planning-KRG
Ministry of Environment-KRG

Subject: Request for information on effect of drought on Iraqi Water Resources.

Dear Sir,

We have a few Iraqi students working towards their PhD degree under my supervision here at the University of Salford, Greater Manchester, UK. We highly appreciate if you could help us in gathering some of the information related to drought and available water resources in Iraq. The information we may need include:

1. All available local studies done to analyse drought impacts on Diyala basin corresponding the agriculture, domestic, industrial as well as local communities ,
2. All available FAO and other UN organizations' works that have been carried out corresponding drought in Diyala basin in the agriculture, domestic, industrial as well as local communities.
3. Actions that were took by local authorities to tackle and mitigate the drought influences corresponding to the agriculture, domestic, industrial as well as local communities.
4. Tools used to evaluate drought impacts.
5. Early warning drought system if any.
6. Future plan by local agriculture and water authorities to mitigate drought negative effects.
7. Inflow, outflow and pool elevation records of Derbendikhan dam for water years 1990-2012.
8. Meteorological data of climatic stations belong to Derbendikhan and Diyala basin.
9. Free water surface evaporation from Derbendikhan reservoir.

We assure you that any information we collect will only be used for research purposes and we are happy to sign Non-Disclosure agreement with you, if any.

The outcomes of the research may be supplied to you if you want it.

Many thanks and looking forward for your help.

Yours Sincerely,

T. Devi 1$/03/2013 .

(Dr Prasad Tumula)
Senior Lecturer | School of Computing, Science and Engineering
Newton Building, University of Salford, Salford M5 4WT, UK
t: +44 (0) 161 295 3644
Email address | d.p.tumula@salford.ac.uk
Web: www.salford.ac.uk

School of Computing Science & Engineering
11 MAR 2013
University of Salford

Agreed

DG Dams/KRG

18-03-2013
Akram A. Rasul

Appendix 2 Request for Data - MoAgWR-KRG-Sulaimaniya Irrigation Directorate

University of Salford MANCHESTER

School/Department: Civil Engineering
College: College of Science and Technology
Contact details: Dr. Devi Prasad Tumula, Senior Lecturer, Civil Engineering Directorate.

Web address: http://www.salford.ac.uk

Date: 02/04/2013

To Whom It May Concern

To,
Ministry of Agriculture and Water Resources - KRG - Sulaymaniyah Irrigation Directorate

Subject: Request for information on effect of drought on Iraqi Water Resources.

Dear Sir,

We have a few Iraqi students working towards their PhD degree under my supervision here at the University of Salford, Greater Manchester, UK. We highly appreciate if you could help us in gathering some of the information related to drought and available water resources in Iraq. The information we may need include:

1. Sharazour irrigation project
2. Qara Ali dam and irrigation project
3. Daradwen dam (D/S derbandikhan dam)
4. Bawanoor dam (D/S Derbandikhan dam)
5. Kaokos (D/S Derbandikhan dam)
6. Small farms U/S Derbandikhan dam
7. proposed and planned irrigation projects U/S and D/S Derbandikhan dam
8. Daily and Monthly records for precipitation, Temperature, Humidity, wind Speed, evaporation for climatic stations in Sulaymaniyah.
9. Hydrological studies about Tanjero river, Zalam and other small streams.
10. Drought events and records in Sulaymaniyah .

We assure you that any information we collect will only be used for research purposes and we are happy to sign Non-Disclosure agreement with you, if any.

The outcomes of the research may be supplied to you if you want it.

I agree

Many thanks and looking forward for your help.

Yours Sincerely,

P. Devi Prasad 02/04.

School of Computing, Science & Engineering
02 APR 2013
RECEIVED

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بەڕێوەبەر
بەروار: / / ٢٠

(Dr Prasad Tumula)
Senior Lecturer | School of Computing, Science and Engineering
Newton Building, University of Salford, Salford M5 4WT, UK
t: +44 (0) 161 295 3644
Email address | d.p.tumula@salford.ac.uk
Web: www.salford.ac.uk

School of Computing
Science & Engineering
02 APR 2013
University
of Salford

Appendix 3 Published papers and papers in review