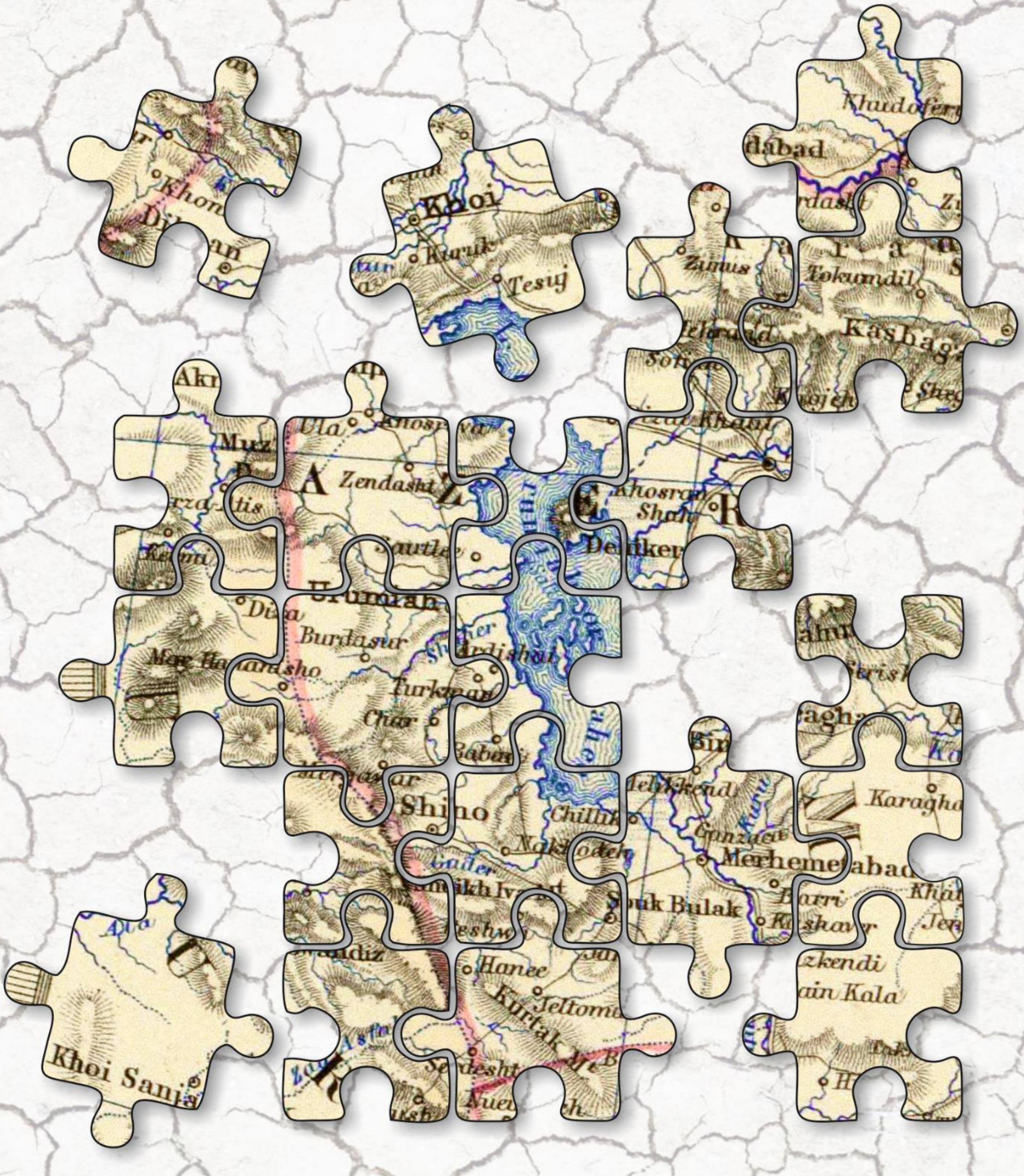
PRESERVING URMIA LAKE IN A CHANGING WORLD:

Reconciling anthropogenic and climate drivers by hydrological modelling and policy assessment

Somayeh Shadkam



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Abstract

Urmia Lake, in north-western Iran, is an important internationally recognized natural area designated as a RAMSAR site and UNESCO Biosphere Reserve. Over the last 20 years, the surface area of Urmia Lake has declined by 80%. As a result, the salinity of the lake has sharply increased which is disturbing the ecosystems, local agriculture and livelihoods, regional health, as well as tourism, which could amplify economic, political and ethnic tensions in this already volatile region. In response to that, Iranian government established the ten-year "Urmia Lake Restoration Program (ULRP)" proposing six approaches in terms of controlling, protecting, surveying, studying and supplying water from other sources. This study first assessed the main reasons for the decreased inflow using the Variable Infiltration Capacity (VIC) hydrological model, including reservoirs and irrigation modules. The results showed that climate change was the main contributor to this inflow reduction. However, water resources development, particularly water use for irrigation, has played a substantial role as well. In the second step assessed Urmia lake inflow under future climate change and irrigation scenarios. Then, the (VIC) model was forced with bias-corrected climate model outputs for both the lowest (RCP2.6) and highest (RCP8.5) greenhouse-gas concentration scenarios to estimate future water availability. The results showed that the water resources plans are not robust to changes in climate. In other words, if future climate change is limited due to rapid mitigation measures (RCP2.6) the new strategy of reduction of irrigation water use can contribute to preserve Urmia Lake.

The next step of this study assessed the quantitative impacts of ULRP by introducing a constructive framework. The framework depicts real water saving by distinguishing between water withdrawals, depletion, and demand in the context of uncertainties in future demand and supply. The results showed that although the ULRP helps to increase inflow by up to 57% it is unlikely to fully reach its target for three main reasons. The first reason is decreasing return flows due to increasing irrigation efficiency. The second reason is increased depletion which is due to neglecting the fact that agricultural water demand is currently higher than available water for agriculture. The third reason is ignoring the potential impact of climate change. However, there still can be some additional none-quantifiable barriers and challenges that may cause the failure of the restoration plan. Therefore, in the last step, this study used two types of qualitative data to explore these aspects: first, the opinions from 40 experts and the in-situ observation of some of the ULRP implementation practices. The results indicate a number of challenges for the ULRP implementation including the water use regulations and the agricultural measures. In addition, (water) demand-side measures such as crop pattern changes were more supported, as opposed to supply-side measures.

This thesis showed that the sustainable approach to preserve Urmia Lake should incorporate both demand management (considering socioeconomic complexity) and flexible supply management strategies (to deal with uncertainties in climate variability and change) in a participatory approach. To be prepared for the future, also scenarios with reduced inflow into Urmia Lake, either due to climate change or water resources development, need to be considered to deal with considerable amounts of variability in the current system and with future changes in climate and socioeconomic conditions.

CONTENT

CHAPTER 1:
Introduction

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Introduction

1.1. Impact of climate and water resources developments on natural environments in water stressed areas

Growing population, expanding irrigated area, and industrial development have driven an ever-increasing demand for water worldwide (Sterling et al., 2013). Irrigation is the major user of water and accounts for 70% of the total use (Döll and Siebert, 2002). In addition, thousands of reservoirs have been constructed in many rivers to increase water availability (Pekel et al., 2016, Hansen and Cramer, 2015). In addition to growing demand, both climate change[1] and variability have a significant impact on the natural hydrological cycle and amplify water scarcity in (semi)-arid regions (Haddeland et al., 2014, Fernandes et al., 2011, Santos et al., 2014). Consequently, water demand has approached or is approaching water availability in many basins, also referred to as basin closure (Molle et al., 2010). This leaves limited volumes of water for the natural environment (Karimi, 2014). Therefore, managing water for a growing population without having devastating effects on natural resources is becoming a serious challenge in many basins worldwide.

An increasing number of drying (hyper)-saline lakes, which has been known as Aral Sea syndrome (AghaKouchak et al., 2015), is an example of this challenge. The Aral Sea has been steadily shrinking after diverting its feeding rivers for irrigation projects (Micklin, 1988). The Aral Sea desiccation caused considerable negative ecological and biological impacts, including devastation of local species, disturbing local communalise by dust and salt storms and changing the climate of the surrounded areas (Micklin, 2007). Lake Poopó in Bolivia (Seiler, 2014), Owens Lake, in California, USA (Costa-Cabral et al., 2013), and Hamun Lake on the Iran-Afghan border (UNDP, 2014) are among other (hyper)-saline lakes around the world which have also decreased in size and increased in salinity. The reported effects are geographically widespread, mostly irreversible and have resulted in degraded ecosystems (Hammer, 1986).

Climate change is likely to increase pressure on different sectors, along with the ecosystem (semi)-arid areas (Vörösmarty et al., 2010). Moreover, water demand, especially for irrigation, is also often increasing in these areas (Figure 1-1), which will be even more pronounced with increasing global warming (Haddeland et al., 2014). These show that future water resources developments and climate

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[1] *In this study climate change is defined as follows: "A change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity" IPCC Fourth Assessment Report 2007: Climate Change: Synthesis Report.*

change, which are inextricably interlinked, are likely to increase pressure on natural environments even more. Therefore, to preserve threatened natural resources in water stressed areas, an integrated assessment which takes into an account both climate and water resources development impacts are needed. Impact assessments that do not account for the interactions between these two main drivers have the pitfall to misrepresent impacts. Such misrepresentation is likely to be reflected in an over- or underestimation of impacts (Harrison et al., 2016). However, there is little information available on integrated climate impacts in regional scales (IPCC, 2014a), which might be due to lack of appropriate tools and data. This lack is a major barrier in developing successful evidence-based strategies to preserve natural resources (Harrison et al., 2016).

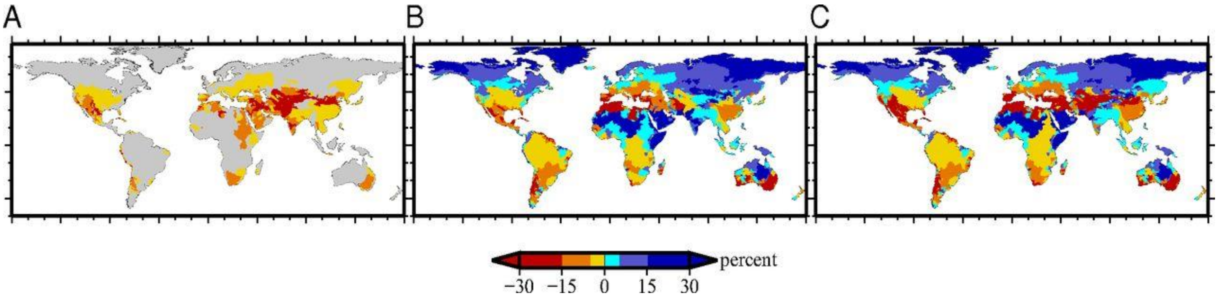


Figure 1-1 Comparison of human impact and climate change effects on runoff at the river basin level. Basin averaged runoff values are calculated based on simulated discharge at the outlet of the river basins, and the median ensemble results are shown. (A) Control period (1971–2000) human impact simulations compared with control period naturalized simulations. (B) Basin averaged naturalized runoff for moderate levels of global warming, compared with control period naturalized simulations. (*C*) Basin averaged human impact runoff for moderate levels of global warming, compared with control period naturalized simulations (Haddeland et al., 2014).

1.2. Strategies to save water for natural environments in water stressed area

During the last century, water management strategies have mostly focused on developing water resources to secure food and energy for a growing population, and have mostly ignored water needs for the environment. Degraded wetlands and lakes, ground water depletion and reduced ecosystem services are some of the consequences of these policies. To prevent further environmental degradation and to promote resilience to drought, water saving strategies have been introduced to the environmental policy agenda in many (semi)-arid regions. Wada et al. (2014) assessed six strategies to reduce water stress, namely agricultural water productivity, irrigation efficiency, improvements in domestic and industrial water-use intensity, limiting the rate of population growth, increasing water storage in reservoirs and desalination of seawater. Their results showed that in most basins under water stress at least five of the six strategies can reduce water stress significantly by 2050. However, all strategies require strong commitment by the involved stakeholders and each also has related complexities, in particular the strategies focusing on reducing water demands. A number of additional water-stress measures are also possible, such as decreasing evaporation from wet soils, development of more water-efficient dietary patterns, an expansion of importing agricultural goods (or ‘virtual water’) and inter-basin transfer (Sun et al., 2015, Karimi et al., 2013b, Wada et al., 2011), although some of these strategies may be unsustainable and have some negative socio-environmental consequences. These unsustainable strategies should only be applied temporarily when more sustainable approaches are under development (Wada et al., 2014).

Some case study assessment showed that the implementation of these water-saving policies are not always straightforward and may not only fail to reach their goals to reduce water stress but also reduce basin resilience through loss of flexibility and redundancy (Scott et al., 2014). Existing water-saving strategies often ignore possible changes in future water availability and demand, and interactions between them. It is also possible that an increase in efficiency in resource use causes an increase (rather than decrease) in resource consumption (Berbel et al., 2015). This is known as the rebound effect and has been reported in relation to many water saving investments (Gómez and Pérez-Blanco, 2014, Qureshi et al., 2010, Peterson and Ding, 2005, Contor and Taylor, 2013, Soto-García et al., 2013). An illustration of this rebound effect is the promotion of irrigation efficiency in order to save water for the environment. Although increasing irrigation efficiency often reduces withdrawals, it also decreases return flows which often reduces downstream water availability (Scott et al., 2014, Lankford, 2012, De Graaf et al., 2014). Although quite well-described in literature, the dynamic effect of these complexities is not always adequately addressed in strategies aiming to save water for the environment. In addition, water-saving strategies often get involved with some hard-to-quantify challenges and barriers, which can make the strategies less feasible. These problems need to be identified through a qualitative approach. This implies a need for an additional assessment based on perspectives or mental models along with the technical assessment to deal with the other perspectives on the problem (Kim et al., 2013). Such an assessment can be realized by combining qualitative (soft) and quantitative (hard) approaches (Pahl-Wostl, 2007). In the absence of an adequate assessment, water saving policies may even aggravate water scarcity and put more pressure on natural resources (Scott et al., 2014, Törnqvist and Jarsjö, 2012, Gleick et al., 2011).

This thesis focuses on preserving endangered natural environments in area of water stress. Regarding the two main research gaps discussed above, the study delivers an integrated assessment of the impact of water resources development and climate variability and change on declining required water for natural environment. Further, the thesis assesses the effectiveness and feasibility of strategies aiming to save water to preserve natural environment. As the case study the thesis selected Urmia Lake, a highly degraded hyper-saline lake in north-western Iran. Urmia Lake basin has been selected, firstly because of the need for an urgent care due to its highly vulnerable ecosystems and irreversible socio-environmental impacts of its desiccation. Secondly because of the availability of restoration program which aims to save water to restore and preserve the lake in a sustainable way.

1.3. Urmia Lake

For our study, we selected one of the areas most affected by both climate variability and change and water resources development, Urmia Lake basin in northwestern of Iran (Figure 1-2). Urmia Lake used to be one of the largest permanent hypersaline lakes in the world and the largest lake in the Middle East. The lake was declared a Wetland of International Importance by the Ramsar Convention in 1971 and designated a UNESCO Biosphere Reserve in 1976 (Eimanifar and Mohebbi, 2007). However, the lake's water level and surface area have sharply declined over the last decades (Kakahaji et al., 2013).

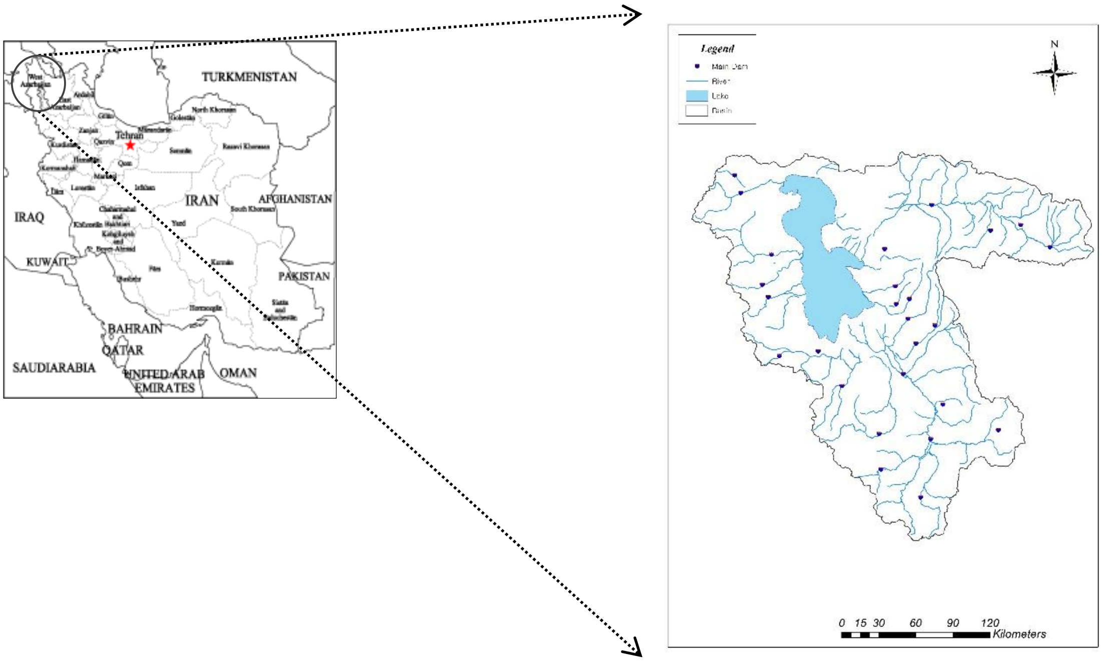


Figure 1-2 a) The location of Urmia basin in northwest Iran, b) Urmia basin with the location of the main dams and rivers

Abbaspour and Nazaridoust (2007) considered 240 g/l of NaCl as the water quality threshold for the survival of Artemia urmiana, the key species living in the lake. By using a long-term record of the Lake water level and NaCl concentration data, they estimated the water level of 1274.1m a.m.s.l. as the lake ecological level. The lake experienced the lowest ever recorded level in October 2015, 1270.04 m a.m.s.l., which negatively affects normal ecological functions of the Lake, including Artemia reproduction and supporting biodiversity. This has caused an environmental disaster by increased salinity and disturbing the basin ecosystem, local agriculture and livelihoods, and regional health (Golabian, 2011). Several studies have warned that the future of Urmia Lake could become similar to that of the Aral Sea, which has dried up over the past several decades and severely affected the surrounding people with windblown salt storms (Torabian, 2015). The population around Urmia Lake, however, is much denser compared to the Aral Sea and many more people are at risk (UNEP, 2012). Local reports have indicated that thousands of people around the lake have already abandoned the area (RadioFarda, 2014). It has been estimated that people living within 500 km of the Lake location are at risk (Torabian, 2015), which could amplify economic, political and ethnic tensions in this already volatile region (Henareh et al., 2014).

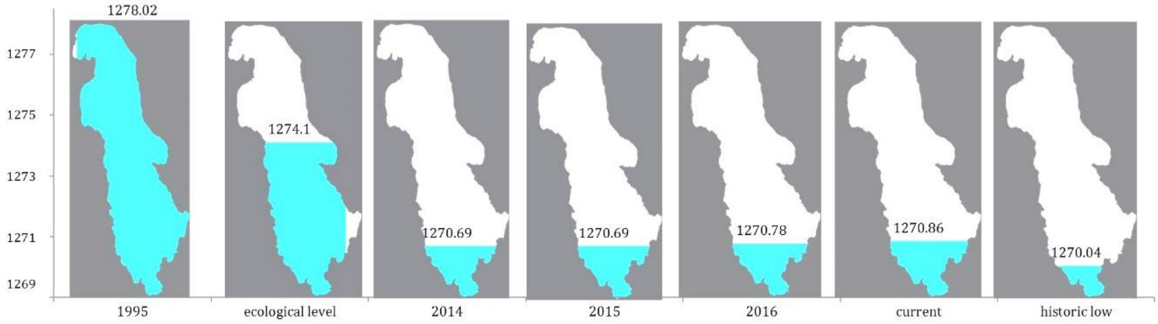


Figure 1-3 The lake surface area from 1995 to current (January 2017) compare with ecological level, the lowest recorded lake level was 1270.04 above mean sea level (amsl) (October 2015) (ULRP, 2017)

1.3.1. Causes of Urmia Lake Desiccation

The area of agricultural land in the Urmia basin has more than tripled over the last 40 years, supported by a considerable number of reservoirs and a large irrigation network (Iran Ministry of Energy, 2014i). Forty-one small and large reservoirs have been built in the basin since 1970 (Figure 1-1), storing around $2000\times10^6 m^3$ water and about 510,000 ha of irrigated land in the basin with 33 modern and traditional irrigation networks. There has also been a significant decrease in precipitation and an increasing trend in the average maximum temperature in the same period (Fathian et al., 2014, Delju et al., 2013) which has caused the basin climate classification to change from semi-arid climate to arid (Arkian et al., 2016). These changes in the basin climate have caused the most extreme droughts in the basin over the last few decades during the mid-1990s (Tabari et al., 2013). These changes have affected the inflow into the lake (Fathian et al., 2014) which has been recognized as the main reason of the lake shrinkage (Hassanzadeh et al., 2012). Farokhnia (2015) compared the impact of climate change and human water use on Urmia Lake inflow and their results indicated that climate change was the dominant reason to reduce the lake inflow. Fathian et al. (2014) also showed the correlation between inflow reduction and climate variability (precipitation and temperature). On the other hand, by assessing satellite-based precipitation data AghaKouchak et al. (2015) suggested that human water use has been the most influential factor on the lake desiccation. Although the studies mentioned indicated different factors to be the major contributor to the declining inflow, they all agree that a combination of climate change and water resources development has caused the observed decline. However, there is a very little information about the relative contributions of these two drivers so far and it is therefore not clear to what extent climate change and water resources development have contributed to the declining inflow. In addition, the global studies illustrated the important role of future climate change in the region which is likely to reduce the precipitation and run-off in both near-term (Kirtman, 2013) and long-term future (Collins, 2013). However, there has been no study to assess the role of climate change and water resources management on the future of the lake to see how and in which future scenarios it is possible to restore the lake. This makes it difficult to develop a robust plan to restore and preserve the lake.

1.3.2. Urmia Lake Restoration Program

Due to the worsening lake conditions and national and international pressures, the government of Iran announced a 10 years intervention named “Urmia Lake Restoration Program” (ULRP) to restore and preserve the lake. Thereafter, the government committed a budget of five billion US dollars for this purpose (Guardian, 2015). The vision of the program is to revive the Urmia Lake life cycle and promote integrated water resources management and sustainable agricultural development in the Urmia Lake Basin. ULRP proposed six approaches in terms of controlling, protecting, surveying, implementing software and hardware projects and supplying water from other sources (ULRP, 2017). However, it is still unclear to what extent ULRP, which has just started and is going to have large socioeconomic impacts, will be able to restore and preserve the lake under future climate change and socioeconomic development.

This thesis focuses on the impacts of climate variability and change and water resources development, namely reservoirs operation and irrigation expansion, on the lake inflow using a simulation approach. Although desiccation of the lake can also be affected by other factors like precipitation and evaporation, this study focused on the inflow reduction as the main driver of the lake desiccation. In addition, this study evaluates the Urmia Lake Restoration Program under different climate change and socioeconomic scenarios applying quantitative and qualitative approaches.

1.4. Research objectives and questions

This thesis aims to assess the challenges of preserving endangered natural environments in areas of water stress. Urmia Lake has been selected as the case study due to its critical condition. Two main objectives are therefore defined for this study. The first objective is to assess the impacts of climate change and water resources management, as the main influential, on Urmia Lake inflow. Secondly, this thesis assesses the effectiveness and feasibility of Urmia Lake Restoration Program (ULRP), as a water-saving policy, to restore the lake. To address the objectives, four research questions have been formulated:

1. What are the combined and discrete effects of climate variability and change, and water recourses development on Urmia Lake inflow?
2. How is it possible to preserve Urmia Lake under future climate change and water resources development?
3. What is the expected quantitative impact of ULRP on Urmia Lake inflow?
4. To what extent are ULRP measures effective and what are the implementation challenges?

To answer these questions an integrated, cross-sectoral assessments approach was applied to account for the indirect impact of climate change and to prevent over-or underestimation of impacts (Harrison et al., 2016). Therefore, along with climate change scenarios, the study took into account agricultural water resources management and socioeconomic scenarios. The answers to these questions will help us to better understand the challenge of preserving endangered natural resources under future change.

1.5. Methods

1.5.1. Hydrological model

Hydrological models have been developed to study processes influencing streamflow and to simulate estimates for other time periods or spatial extents than in the available data. Therefore, hydrological models can be used for scenario analyses, such as climate change impact assessments (Vliet et al., 2012c). Several macroscale hydrological models have been developed to advance understanding of the hydrological cycle and its interaction with land surface and substrate, and to simulate potential effects of climate change on hydrological fluxes (Vliet et al., 2012a). However, macroscale hydrology models traditionally simulate naturalized streamflow, i.e. the simulations do not take reservoirs, diversions, or water withdrawals into account. Hence, in river basins having significant reservoir storage capacity and irrigated lands, like Urmia basin, simulated discharge does not match observed discharge (Haddeland et al., 2006).

Therefore, the Variable Infiltration Capacity (VIC) model, including reservoir and irrigation modules was used in this study (Figure 1-3), which has the ability to simulate the impacts of reservoirs and irrigation. The VIC model is a grid-based soil–vegetation–atmosphere transfer scheme model (Liang et al., 1994, Nijssen et al., 2001b, Nijssen et al., 1997). The input data are precipitation, maximum and minimum temperature and wind speed. Each grid cell is divided into multiple vegetation types and into multiple soil layers (Figure 1-3-a). Historical vegetation data were obtained from the SAGE database at the University of Wisconsin-Madison (available online at http://www.sage.wisc.edu/). Evapotranspiration is calculated using the Penman-Monteith equation. The simulated surface streamflow and base flow, combined referred as inflow in this paper, are routed from each grid cell (Figure1-3-b) to the basin as described by Lohmann et al. (1998a, 1998b). The VIC model, like most land surface models, does not consider deep groundwater withdrawals (Haddeland et al., 2007), which therefore are not taken into account in this study. The model has been widely used for streamflow studies globally (Nijssen et al., 2001a, Vliet et al., 2013) and for major river basins, as well as for other parts of the world like Europe, the US, and China (Hurkmans et al., 2008, Xie et al., 2007a, Wu et al., 2007, Vliet et al., 2012b). The results of these studies have shown that the model has been able to reproduce the water cycle under a range of different climates.

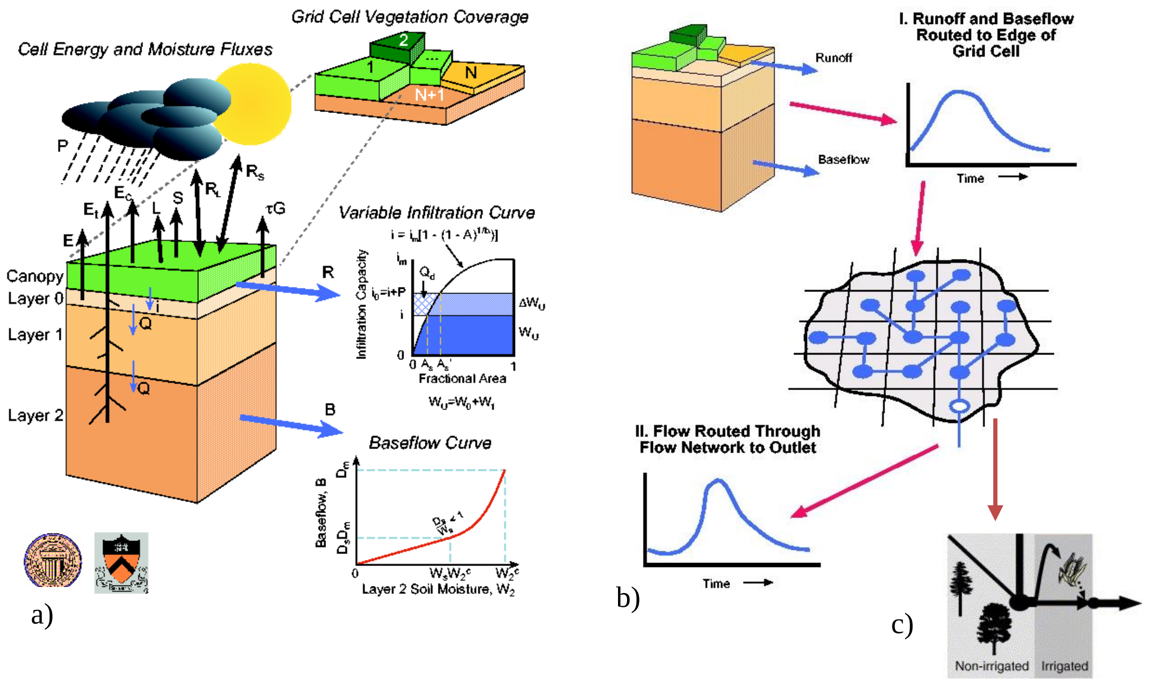


Figure 1-4 (a) Variable Infiltration Capacity (VIC) hydrological model, (b) the VIC river network routing model (source: website University of Washington, http://www.hydro.washington.edu/Lettenmaier/Models/VIC/). (c) VIC irrigation scheme (source: Haddeland et al., 2006)

Haddeland (2006) added reservoir and irrigation schemes to the VIC model, allowing the model to simulate irrigation water use, based on the calculated soil moisture deficit. The crop evapotranspiration is first calculated within the grid cells based on FAO (Food and Agriculture Organization of the United Nations)'s guideline (Allen et al., 1998). The grid cells are divided into an irrigated and a non-irrigated area (Figure 1-3-c). In the model, irrigation is initiated if soil moisture falls below the transpiration level. To calculate irrigated water demand, an initial model run is performed assuming unlimited irrigation water availability. Thereafter, a simulation run is performed where irrigation is limited by water available from local river runoff, and, if no runoff water is available, water is extracted from reservoirs (Haddeland et al., 2006). The reservoir scheme calculates optimal release based on simulated reservoir inflow, storage capacity, reservoir evaporation, and downstream water demands. The optimal released calculated based on the SCEM-UA algorithm (Vrugt et al., 2003). The model was able to simulate well the main hydrologic impacts of reservoir operations and irrigation water withdrawals on streamflow in different parts of the world (Haddeland et al., 2006, Haddeland et al., 2014).

The model information databases are at continental scales, which makes model suitable to run at global or continental scales (Haddeland, 2006). Therefore, it was needed to include local information before applying the model to the Urmia basin. Hence, the following local information on irrigation water use: percentage irrigated area, crop characteristics for each cell, and the cropping calendar were added to the irrigation module. For the reservoir scheme, information for the basin's dams including locations height, storage capacity, operating purpose, irrigating area, and surface area were added to the reservoirs module.

For the historical run (Chapter 2), The model forced with global gridded half-degree meteorological Watch Forcing Data (WFD) (Weedon, 2011), 1958-2001, and Watch Forcing Data ERA-Interim (WFDEI) (Weedon et al., 2014), 1979-2010. The simulation was performed for five different runs. The first run simulated conditions without reservoirs and irrigation (naturalized flow). The second run only simulated reservoir operation in the basin (only reservoir run). To calculate water demand, the third run assumed irrigation water is freely available (free irrigation run). In the fourth run irrigation was limited by water available from local river runoff, and, if no runoff water was available, water was extracted from reservoirs (limited irrigation run). The last run considered both reservoirs and irrigation in the basin (irrigation and reservoir run).

The model was forced further with Bias-corrected daily climate model output as developed within the Inter-Sectoral Impact Model Intercomparison Project (Hempel et al., 2013, ISI-MIP, Warszawski et al., 2014) for the future run (Chapter 3). To cover the whole range of future greenhouse gas emissions we selected the highest (8.5) (Riahi et al., 2011) and the lowest (2.6) (Van Vuuren et al., 2011) RCPs. In addition to using naturalized flow (‘naturalized’), the first scenario, and a continuation of the current water management (‘current_irrig/res’), the second scenario, two additional anthropogenic scenarios based on two recent official water management plans were used. Therefore, the third scenario assumes an expansion of the dams and reservoirs (‘expansion_irrig/res’). The forth scenario aims at restoring the lake and reduces future irrigation (‘reduction_irrig’) and stops all reservoirs and irrigation development. To see if it is possible to restore the lake under different climate change and water resources management scenarios, the simulated inflows were compared with the lake Environmental flow Requirements (EFRs).

1.5.2. Urmia Lake Restoration Programme assessment

Several frameworks have been proposed to report basins water-related information in a structured way (UN, 2003, Hoekstra et al., 2009, Karimi et al., 2013a). However, none of the frameworks were specifically designed to assess a water-saving intervention. In the absence of an adequate basin-wide assessment tool, water saving policies may even aggravate water scarcity and put more pressure on natural resources (Scott et al., 2014, Törnqvist and Jarsjö, 2012, Gleick et al., 2011). Therefore, in this thesis, I introduce a comprehensive framework for assessing water-saving interventions. The framework depicts real water saving by distinguishing between water withdrawals, depletion and demand in the context of uncertainties in future demand and supply. The framework with a more detailed description of the water-saving intervention assessment is presented in Chapter 4. The framework has been applied to the situations “ex ante” and “ex post” of the interventions under different climate change and socioeconomic scenarios.

Although quantitative approaches are essential in any policy assessment they can only account for what can be quantified in a credible way, and thus provide only a partial insight in what usually is a very complex mass of uncertainties, assumptions, and ignorance (Van Der Sluijs et al., 2005). Policy decisions need to be made before conclusive scientific evidence on these problems is available, while at the same time the potential error or hidden barriers can cause a failure or huge cost (Van Der Sluijs et al., 2005). This implies a need for an additional assessment based on perspectives or mental models along with the technical assessment to deal with the other perspectives on the problem (Kim et al., 2013). Such an assessment can be greatly facilitated by combining qualitative (soft) and quantitative (hard) approaches (Pahl-Wostl, 2007). In general, qualitative methods include presentation of individual lines of evidence without an attempt at integration based on qualitative considerations (Linkov et al., 2009). The input for qualitative analysis generally results from experts' judgments, qualitative fieldwork experience, interviews, observations, and documents (Patton, 2005). The experts are the best qualified individuals in any field of study and their opinions are used in intellectual analysis, in order to clarify definitions, identify challenges, or make a value judgment concerning an issue in their field of study (Creswell, 2013). The experts' opinions are reported in a structured and sometimes quantitative form. The results can further be discussed with observer impression. That is, expert or bystander observers examine the data, interpret it via forming an impression (Seyama and Nagayama, 2007).

Therefore, this thesis applies a qualitative approach to assess ULRP to give a holistic picture of feasibility, challenges and barriers of ULRP measures. To do so, the opinions of 40 experts concerning the ULRP measures have been collected and prioritized. This was followed by the author's three field visits to the Urmia basin, collecting local insights on the implementation of the ULRP measures. Blending insights based on experts' judgment field observations, interviews and related literature. This approach provides a qualitative analysis of the ULRP. Along with the quantitative assessment, this study provides a comprehensive assessment regarding the effectiveness and challenges of the Urmia Lake Restoration Program.

1.6. Thesis outline

The objectives and research questions are addressed in four scientific chapters (Chapters 2 to 5). An overview of the research steps and corresponding chapters is shown in Figure 1-5. To answer the first research question, the Variable Infiltration Capacity (VIC) model irrigation and reservoirs modules were regionalized, calibrated and applied for Urmia basin. I estimated the relative contributions of climate change and water resources development - which includes construction of reservoirs and expansion of irrigated areas - to changes in Urmia Lake inflow over the period 1960-2010 (Chapter 2). Then, the model was forced with bias-corrected climate model outputs for both a low (RCP2.6) and a high (RCP8.5) greenhouse-gas concentration scenario to estimate future water availability and impacts of water management strategies (Chapter 3). To answer the second question, I first estimated Urmia Lake Environmental Flow Requirements (EFR), by adapting the mean monthly flow method for hypersaline lakes. The estimated monthly and annual EFR were compared with simulated inflow derived from VIC irrigation and reservoirs modules under different climate change and agricultural water resources management scenarios to see how and in which scenarios lake can be preserved (Chapter 3). To answer the third question, I introduced a constructive framework to assess the water-saving interventions by estimating five components: 1) *Total water demand* under socioeconomic scenarios, *2) Water supply* under climate change scenarios, 3) *Water withdrawal* for different sectors, 4) *Water depletion* and 5) *Environmental flow*. The framework includes climate change and social-economic scenarios and recognition of total water demand and water withdrawals; also, water withdrawals and water depletion. The framework applied to assess ULRP under different climate change and socioeconomic scenarios (Chapter 4). To assess ULRP feasibility and challenges to answer the forth question, I applied a qualitative approach. Two types of qualitative data were used and discussed further. First, 40 experts have been asked to score ULRP measures. Later, the results analysed and discussed based on the author observation from ULRP measures implementation. Finally, in chapter 6, the main results are discussed in a border context, along with the contribution to water management science and policy, and an outlook for future research on this topic.

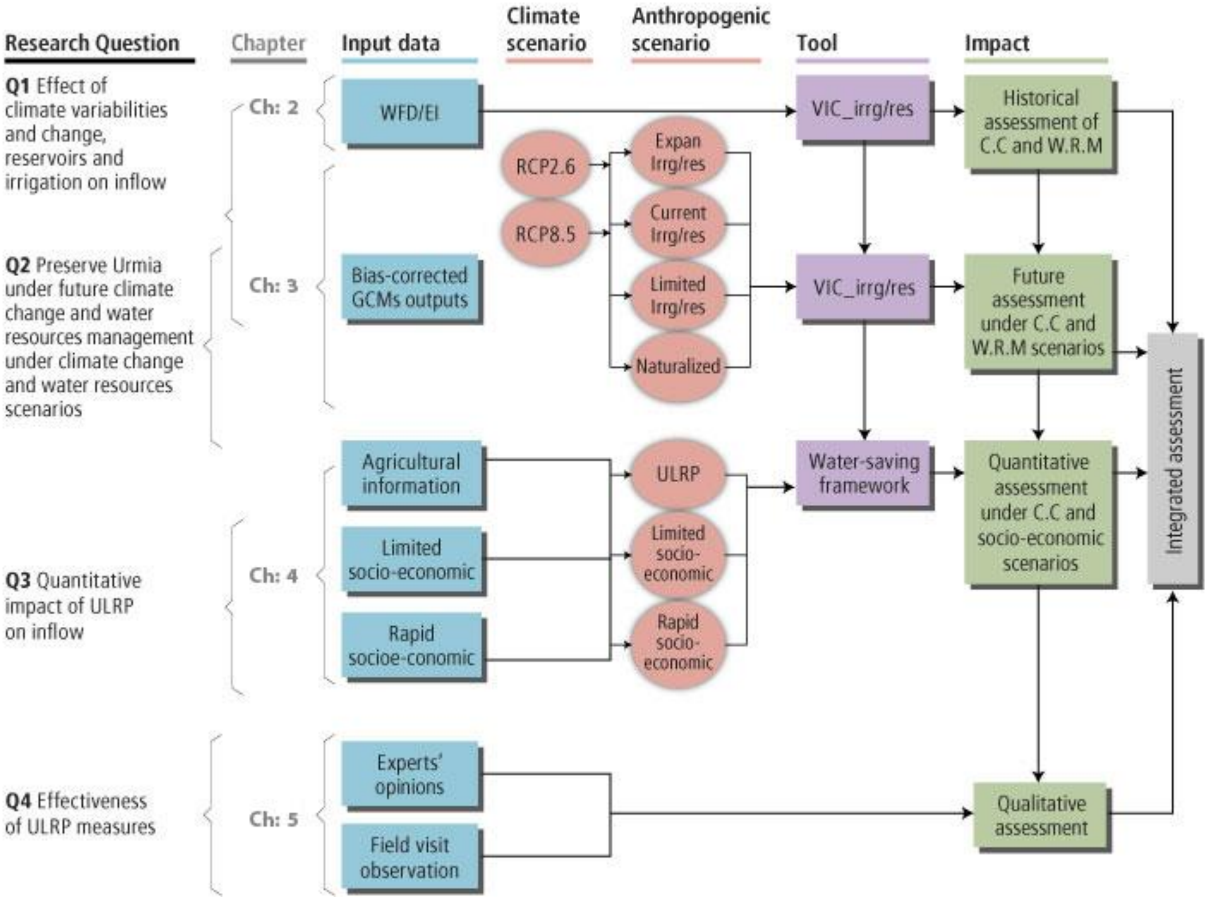
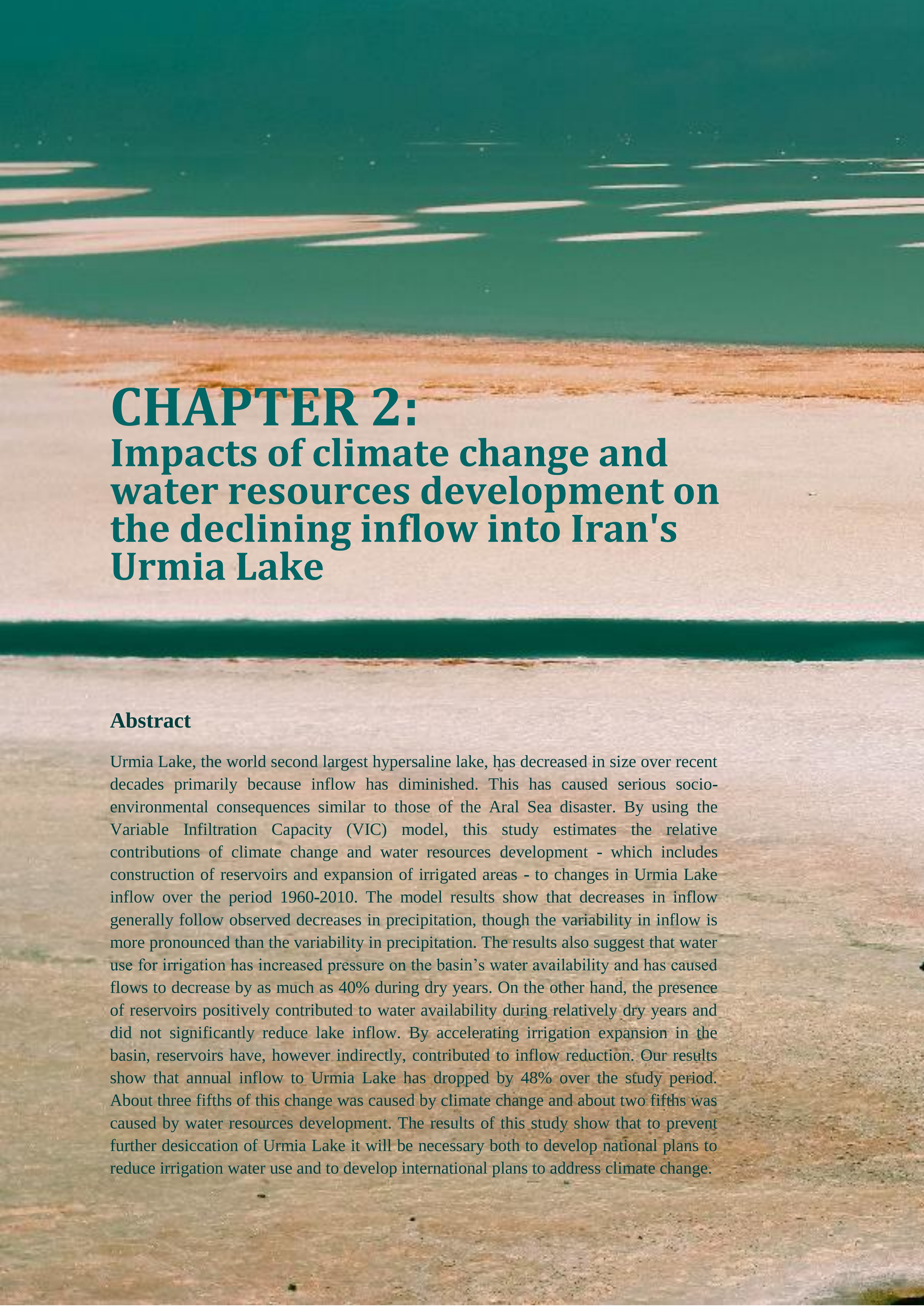


Figure 1-5 Schematic representation of methodological framework with input data, climate, agricultural water resources



CHAPTER 2:

Impacts of climate change and water resources development on the declining inflow into Iran's Urmia Lake

Abstract

Urmia Lake, the world second largest hypersaline lake, has decreased in size over recent decades primarily because inflow has diminished. This has caused serious socio-environmental consequences similar to those of the Aral Sea disaster. By using the Variable Infiltration Capacity (VIC) model, this study estimates the relative contributions of climate change and water resources development - which includes construction of reservoirs and expansion of irrigated areas - to changes in Urmia Lake inflow over the period 1960-2010. The model results show that decreases in inflow generally follow observed decreases in precipitation, though the variability in inflow is more pronounced than the variability in precipitation. The results also suggest that water use for irrigation has increased pressure on the basin’s water availability and has caused flows to decrease by as much as 40% during dry years. On the other hand, the presence of reservoirs positively contributed to water availability during relatively dry years and did not significantly reduce lake inflow. By accelerating irrigation expansion in the basin, reservoirs have, however indirectly, contributed to inflow reduction. Our results show that annual inflow to Urmia Lake has dropped by 48% over the study period. About three fifths of this change was caused by climate change and about two fifths was caused by water resources development. The results of this study show that to prevent further desiccation of Urmia Lake it will be necessary both to develop national plans to reduce irrigation water use and to develop international plans to address climate change.

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CHAPTER 2:

Impacts of climate change and water resources development on the declining inflow into Iran's Urmia Lake

2.1. Introduction

Climate change significantly influences the natural hydrological cycle which can contribute to water scarcity (IPCC, 2014b, Haddeland et al., 2014). To safeguard water and food supplies for growing population, humans construct reservoirs, extract water for irrigation and modify land use. These actions have been associated with an increasing number of drying lakes in arid and semi-arid areas (IPCC, 2014b). However, only a limited number of studies have assessed the role of climate change and water resources development, individually and combined, on the desiccation of lakes. This knowledge gap hampers our ability to develop adequate and effective adaptation strategies to rehabilitate and preserve endangered lakes. Among all vulnerable lakes, the saline and hypersaline lakes need particular attention due to their highly vulnerable ecosystems and the irreversible socio-environmental impacts of their desiccation. In this paper, we evaluate the impact of climate change and water resources development on the desiccation of the world’s second largest permanent hypersaline lake, Urmia Lake (Karbassi et al., 2010).

Urmia Lake basin is located in the northwest of Iran and has been seriously affected by both climate change and water resources development (Jalili et al., 2015, Fathian et al., 2014, Farokhnia and Morid, 2014, Hassanzadeh et al., 2012, Zeinoddini et al., 2009). The Urmia Lake basin is an important agricultural region with a population of around 6 million people. The lake's water level and surface area have sharply declined over the last two decades (Kakahaji et al., 2013). This has caused an environmental disaster by increased salinity and has had negative effects on ecosystems, agriculture, livelihoods, and health (Karbassi et al., 2010). An outcome similar to that observed in the Aral Sea is likely for this lake (Badescu and Schuiling, 2010, AghaKouchak et al., 2015). The Aral Sea has dried up over the past several decades and affected the surrounding communities with windblown salt storms (Micklin, 1988). Moreover, the population around Urmia Lake is much larger than around the Aral Sea and thus more people are at risk (UNEP, 2012).

A number of recent papers have discussed reasons for the shrinkage of Urmia Lake and the possible environmental consequences. Delju et al. (2013) showed how a decrease in precipitation combined with an increase in temperature in the basin has caused the most severe drought in the last 40 years. Other studies have assessed the observed precipitation over the basin and have confirmed the decreasing trend (Hassanzadeh et al., 2012, Farokhnia and Morid, 2014, Rezaei Banafsheh M, 2010, Katiraei PS, 2006, Jahanbakhsh-Asl S, 2003). A recent investigation showed that Urmia Lake only receives a relatively small amount of groundwater discharge (up to 3 percent) so it is very sensitive to the surface inflow fluctuations (Hashemi, 2011, ULRP, 2015a). Hassanzadeh et al. (2012) demonstrated that the decline in surface inflow has been the dominant reason for lake shrinkage. They showed that, in total, 65% of the decline in lake water levels and volumes had been caused by changes in inflow, which was due to surface water use and climate change. Fathian et al. (2014) showed the correlation between inflow reduction and climate variability (precipitation and temperature). They also estimated that inflow to the lake is more sensitive to temperature than to precipitation. On the other hand, AghaKouchak et al. (2015)'s suggested that human water use has been the most influential factor on the lake desiccation. Although the studies mentioned indicated different factors to be the major contributor to the declining inflow, they all agree that a combination of climate change and water resources development has caused the observed decline. However, the relative contributions of these two drivers has not been quantified so far and it is therefore not clear to what extent climate change and water resources development have contributed to the declining inflow. The aim of this paper is to quantify the relative contributions of climate change and water resources development to the declining inflow into Urmia Lake over the last 50 years.

2.2. Study area

The Urmia Lake basin area is around 51,000 km^2, of which the lake formerly covered approximately 5000 km^2. Urmia Lake's water level started to decrease sharply from 1995 (Figure 2-1). Since the lake is shallow (Djamali et al., 2008), the surface area of the lake also shrunk rapidly.

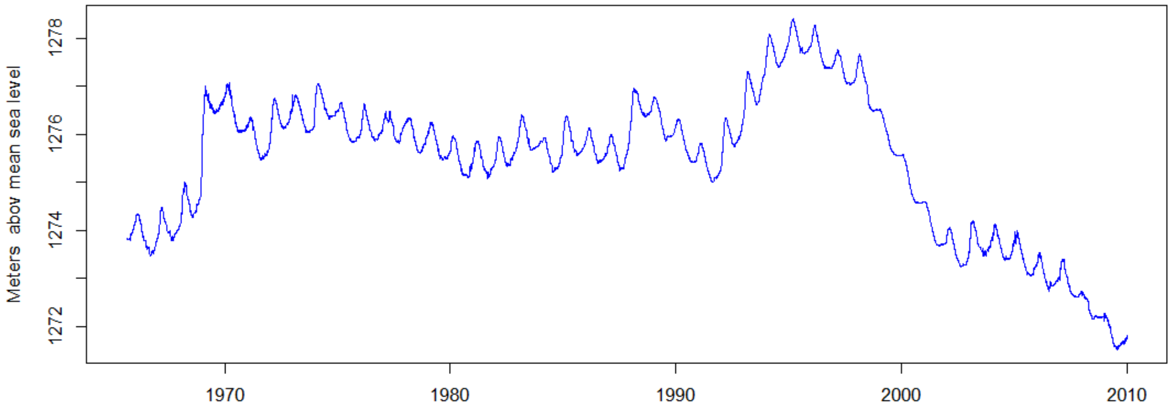


Figure 2-1: Urmia Water level for the period 1965-2010 (data provided by Urmia Lake Restoration Program Program).

There are 17 permanent rivers and 12 seasonal rivers which terminate at Urmia Lake (Figure 2-2). The basin can be divided into six main subbasins: west, southwest, south, east, north, and northeast. The average annual precipitation in the basin is between 300 and 400 mm. The mean annual air temperatures is reported from 6.8 to 14.8°C in summer (Iran Ministry of Energy, 2014i, Karbassi et al., 2010).

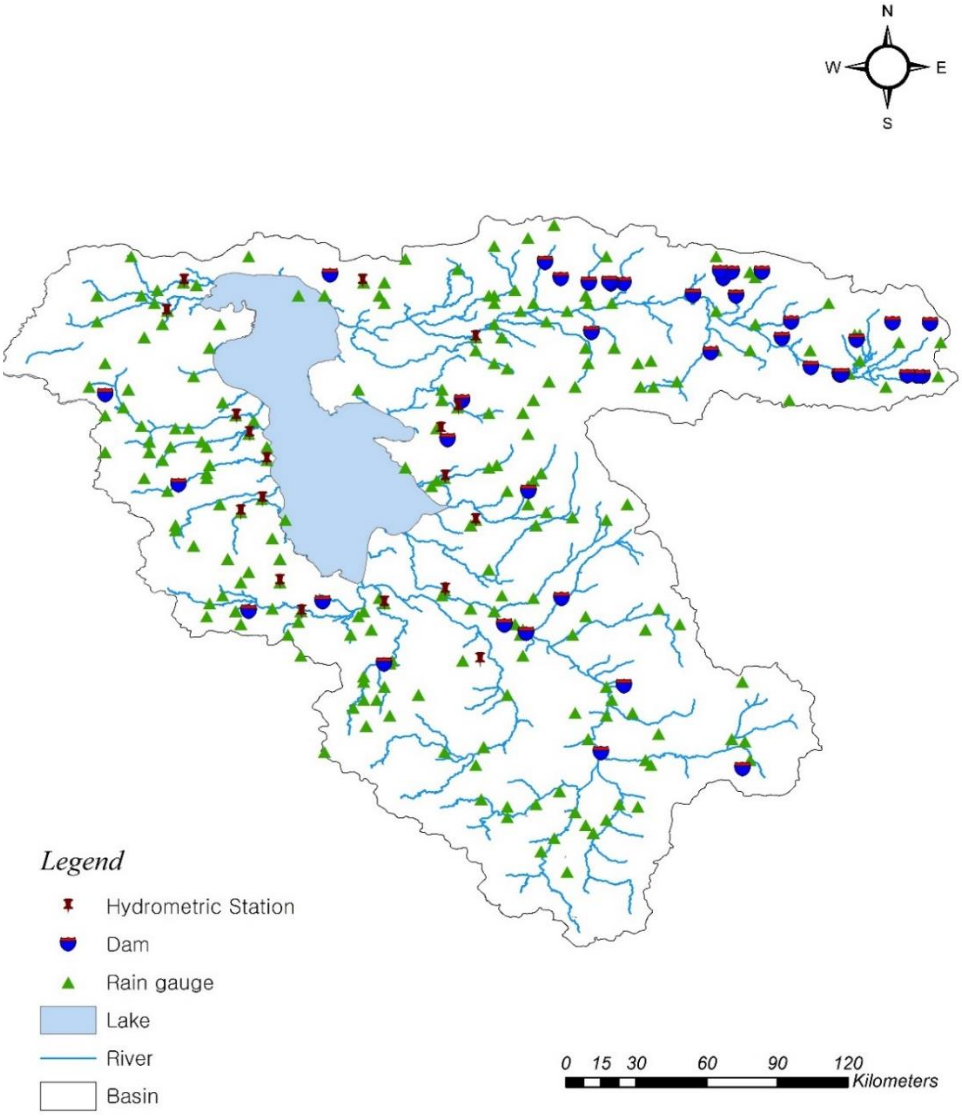


Figure 2-2: the location of dams (41), rain gauge (146) and hydrometric stations (18) in Urmia basin.

The basin has an arid to semi-arid climate; this means that agriculture in the basin is highly dependent on irrigation. There are ~510,000 ha of irrigated lands in the basin with 33 modern and traditional irrigation networks. The reported irrigation efficiency is quite low: 37% for farming and 45% for gardening (Iran Ministry of Energy, 2014f). To support agricultural growth, the area under irrigation around the lake has increased over seven times during the last 15 years (Iran Ministry of Energy, 2014f). These land cover changes along with climate change put extra pressure on the basin's water resources and have caused a dramatic decline in the inflow to the lake (Hashemi, 2011).

Forty-one small and large reservoirs have been built in the basin since 1970 (Figure 2-2), storing around 2000×10^6 m^3 water (Iran Ministry of Energy, 2013b). Information about heights, operating purpose, storage capacities, and surface area of all reservoirs were provided by the Iranian Ministry of Energy, Deputy of Water and Wastewater, Macro Planning Bureau (Iran Ministry of Energy, 2013b).

Of the 511,926 hectares of irrigated lands in the basin, 356,420 hectares (70%) are farms and 155,506 hectares (30%) gardens. The land use, irrigation pattern and cropping calendar information was provided by the Urmia Lake Restoration Program.

2.3. Method

2.3.1. Data management

To assess the precipitation trend during the study period, we used precipitation data from 146 rain gauges distributed over the basin (Figure 2-2). Data quality control and homogenization of precipitation time-series have been done by applying the method described in Vicente-Serrano et al. (2010) as reported by the Iran Ministry of Energy (2014b). This method comprises three steps. The first step filled the data gaps using auxiliary information obtained from Iran Meteorological Organization and nearby observatories. The second step identified the records that differed noticeably from values recorded in neighbouring stations and replaced anomalous and questionable ones. The third step verified the homogeneity of the data series to avoid the presence of spurious data in the final dataset. Observed annual inflow into the lake for the period 1960-2010 was obtained from 18 hydrometric stations located near the outlets of all important tributaries to the Lake (Figure 2-2).

2.3.2. Hydrological model

To separate impacts of climate change and water resources development we used the Variable Infiltration Capacity (VIC) model, including reservoir and irrigation modules. The VIC model is a grid-based soil–vegetation–atmosphere transfer schemes model (Liang et al., 1994, Nijssen et al., 2001b, Nijssen et al., 1997). The input data are daily precipitation, maximum and minimum temperature and wind speed. Each grid cell is divided into multiple vegetation types and into multiple soil layers. Historical vegetation data were obtained from the SAGE database at the University of Wisconsin-Madison (available online at http://www.sage.wisc.edu/). Evapotranspiration is calculated using the Penman-Monteith equation. The simulated surface streamflow and base flow, combined referred as inflow in this paper, are routed from each grid cell to the basin as described by Lohmann et al. (Lohmann et al., 1998b, Lohmann et al., 1998a). The VIC model, like most land surface models, does not consider deep groundwater withdrawals (Haddeland et al., 2007), which therefore are not taken into account in this study. The model has been widely used for streamflow studies globally (Nijssen et al., 2001a, Vliet et al., 2013) and for major river basins, as well as for other basins of the world like Europe, the US, and China (Hurkmans et al., 2008, Xie et al., 2007a, Wu et al., 2007, Vliet et al., 2012b). The results of these studies have shown that the model has been able to reproduce the water cycle well.

Haddeland (2006) added reservoir and irrigation schemes to the VIC model, allowing the model to simulate irrigation water use, based on the calculated soil moisture deficit. The crop evapotranspiration is first calculated within the grid cells based on FAO (Food and Agriculture Organization of the United Nations)’s guideline (Allen et al., 1998a). The grid cells are divided into an irrigated and a non-irrigated area. In the model, irrigation is initiated if soil moisture falls below the transpiration level. To calculate irrigated water demand, an initial model run is performed assuming irrigation water is freely available (free irrigation run). Then, another simulation run is performed where irrigation is limited by water available from the first local river runoff, and, if no runoff water is available, water is extracted from reservoirs (Haddeland et al., 2006). The reservoir scheme calculates optimal release based on simulated reservoir inflow, storage capacity, reservoir evaporation, and downstream water demands.

The optimal released calculated based on the SCEM-UA algorithm (Vrugt et al., 2003). The model was able to simulate well the main hydrologic impacts of reservoir operations and irrigation water withdrawals on streamflow in different parts of the world (Haddeland et al., 2006, Haddeland et al., 2014).

2.3.3. Forcing data

To force the model, we used global gridded half-degree meteorological Watch Forcing Data (WFD) (Weedon, 2011), 1958-2001, and Watch Forcing Data ERA-Interim (WFDEI) (Weedon et al., 2014), 1979-2010. These data sets were specifically developed to be used as meteorological forcing of hydrological models using ERA-40 and ERA-Interim (Dee, 2011) reanalysis through consecutive interpolation to half-degree resolution. The elevation correction and monthly-scale adjustments were done based on monthly observations (Weedon, 2011). As a result of these corrections, the WDF and WFDEI are closer to observations and able to make better assessments of hydrological cycles compared to other available data sets (Weedon et al., 2010).

Both datasets were validated with observed data using a Taylor diagram (Bellocchi et al., 2010, Taylor, 2001, Taylor, 2005) for the overlapping period, 1979 to 2001. The validation was done for precipitation (mm/day), minimum and maximum temperature (°C) for the WFD and WFDEI overlapping period, 1979 to 2001. For precipitation, observed data from 15 stations were used. For maximum and minimum temperature, observed data from seven stations were used. The stations are located homogeneously in the basin and were selected based on data availability for the overlapping period.

2.3.4. Model calibration

We calibrated the VIC model following the methods described by Xie et al. (2007b), using seven runoff-related model parameters, including the infiltration parameter, and the three soil-layer thicknesses. These four parameters were used for the primary calibration. In the advanced stage, the three parameters in the base flow scheme, including the maximum velocity of base flow Dm, fraction of maximum base flow Ds, and fraction of maximum soil moisture content of the third layer Ws, were used.

We calibrated the model for all six subbasins separately, for 1960 to 1970 before the first irrigation and reservoir developments in the basin. After the calibration, we assessed the performance at the stations located furthest downstream, closest to the lake for all six subbasins. To evaluate the accumulation of differences in streamflow volume between simulated and measured data (Moriasi et al., 2007), percent bias (Pbias) was used as an objective function for mean monthly average. The correlation coefficient (R) was also selected to show the degree of linearity between observed and simulated data for the same parameter (Hurkmans et al., 2010).

2.3.5. Simulation and calculations

The model was forced with precipitation, maximum and min temperature and wind speed obtained from WFD for 1960-2001 and WFDEI for 2001-2010. The 0.5 degree spatial and daily temporal resolution have been selected for the simulation regarding the forcing data resolution. Streamflow is simulated by routing subsurface and surface runoff using the method described in Lohmann et al. (1998a).

In order to implement the irrigation scheme, the following local information on irrigation water use was used in the model simulations: percentage irrigated area, crop characteristics for each cell, and the cropping calendar. For the reservoir scheme, information for the basin's 41 dams including the locations, height, storage capacity, operating purpose, irrigating area, and surface area (estimated to be 146 km^2 in total), were added to the model, from which reservoir evaporation was calculated using the Penman equation in the model (Haddeland, 2006).

To ascertain the trend in the impact of reservoir and irrigation development, the relevant input was updated four times during the simulations in four development stages: 1960–1970, when there were no reservoirs in the basin; 1970–1995, when the reservoirs and irrigation area started to expand to 900×10^6m^3 and 370 $\times10^3$ha respectively; 1995–2005, when reservoir capacity increased to 1700×10^6 m^3 and irrigation increased to 430000 ha; and finally 2005–2010, when reservoir capacity increased to 2000×10^6m^3, and irrigation area increased to almost 510000 ha (Figure 2-3). The simulation was performed for five different runs. The first run simulated conditions without reservoirs and irrigation (naturalized flow). The second run only simulated reservoir operation in the basin (only reservoir run). To calculate water demand, the third run assumed irrigation water is freely available (free irrigation run). In the fourth run irrigation was limited by water available from local river runoff, and, if no runoff water was available, water was extracted from reservoirs (limited irrigation run). The last run considered both reservoirs and irrigation in the basin (irrigation and reservoir run).

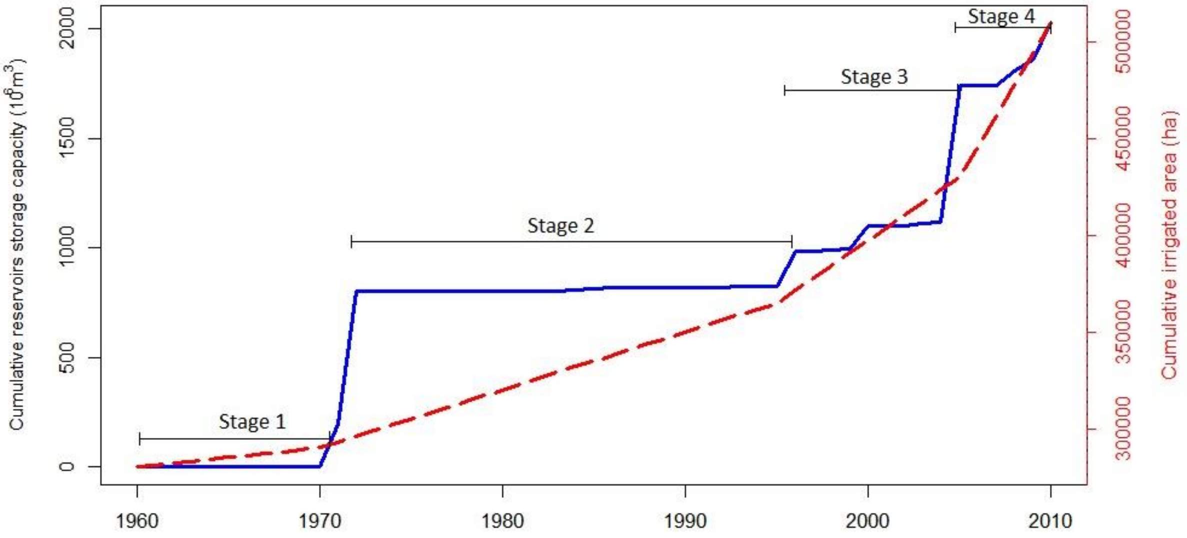


Figure 2-3 The accumulated storage capacity of reservoirs and cumulative irrigation area with four distinguished water resources development stages, 1960–1970, 1970–1995, 1995–2005, 2005–2010, in Urmia basin.

The results were compared to study the role of different factors: climate variability and change, reservoirs, irrigation, and the combination of all factors. Furthermore, by using two approaches, we quantified the effect of climate change and local anthropogenic activities (irrigation and reservoirs) on inflow individually. The first method is based on Wang (2014). By reviewing several methods, he concluded that streamflow can be divided into subseries from a year before human activity is began (baseline period) and after (altered period). Thus, the difference between the mean annual inflow during the altered period and the mean annual inflow during the baseline period (ΔQ)is the total change of inflow which results from the combined effects of climate change and human activity. Based on this rationale, for this study ΔQ can be estimated as:

$$\Delta Q = (\overline{Q_{ap}}) - (\overline{Q_{bp}}) = (\overline{Q_{ap(\imath rr\imath g-res)}}) - (\overline{Q_{bp(nat)}})$$

$$\Delta Q_c = (\overline{Q_{ap(nat)}}) - (\overline{Q_{bp(nat)}})$$ **Equation 1**

$$\Delta Q_h = (\overline{Q_{ap(\imath rr\imath g-res)}}) - (\overline{Q_{ap(nat)}})$$

Where ΔQ_c is change in inflow attributed to climate change, $(\overline{Q_{ap}})$ is the mean annual inflow during altered period, $(\overline{Q_{bp}})$ is the mean annual inflow during baseline period, $(\overline{Q_{bp(nat)}})$ is the mean naturalized annual inflow during the baseline period, ΔQ_h is change in inflow attributed to water resources management development $(\overline{Q_{ap(nat)}})$, is mean naturalized annual inflow during the altered period, and $(\overline{Q_{ap(\imath rr\imath g-res)}})$ is the mean annual simulated inflow including irrigation and reservoirs during the altered period. The results of this approach is compared with another approach, which is based on the differences between the trends of naturalized flow and inflow considering irrigation and reservoirs for the whole 50 years study period.

The Environmental Flow Requirement (EFR) used in this study are based on the study by Abbaspour and Nazaridoust (2007). They considered 240 g/l of NaCl as the water quality threshold for the survival of *Artemia urmiana* the key species living in the lake. By using a long-term record of the lake water level and NaCl concentration data, they estimated the water level of 1274.1m a.m.s.l. as the lake ecological level. Based on the lake surface-volume relation, 4.6×10^9m^2 were estimated as the lake ecological surface area. As Urmia Lake is the terminate lake (no outflow), they concluded that a minimum of 3085×10^6m^3 (the difference between the lake evaporation and precipitation on the estimated ecological surface area) of annual inflow is required to maintain the required ecological level. If the mean annual inflow over a period of several years meets or exceeds the EFR, the lake would continue its normal ecological functions including *Artemia* reproduction and supporting biodiversity. On the other hand, if salinity rises above 240 g/l, these functions would be negatively affected. The estimated EFR, 3085×10^6m^3, has been widely used as a basis for the basin water resources management projects, also defined as the policy target of Urmia Lake Restoration Program (ULRP, 2016b). Therefore, in this study, we compared the simulated inflow to this value.

2.4. Results

2.4.1. Forcing data validation

The Taylor diagram, showing three types of statistical analyses (correlation coefficient, RMSE and standard deviation), was used to compare the WFD and WFDEI with the local observed data (Figure 2-4). The correlation coefficient for precipitation for both WFD and WFDEI is 0.75 which is generally considered to be strong (Bellocchi et al., 2010). The WFD and WFDEI had almost identical RMSE (19 mm/month) and standard deviation (27 mm/month). For minimum temperature, the correlation coefficient for WFDEI is 0.82 and for WFD 0.9. For maximum temperature, the correlation coefficient for WFDEI is 0.87 and for WFD 0.92. The RMSE is higher for WFDEI compared to WFD.

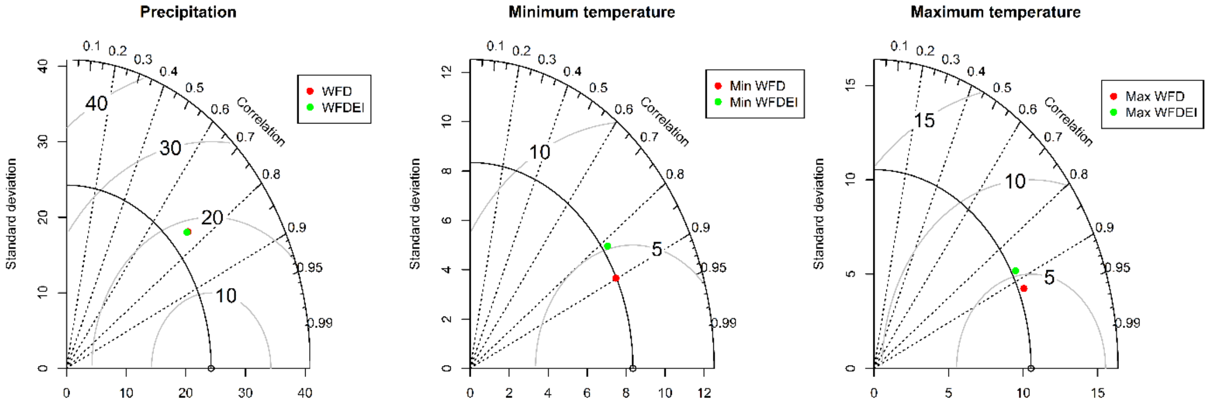


Figure 2-4 Taylor diagram comparing WFD and WFDEI with observed data for a) monthly precipitation (mm/day), b) maximum temperature (°C), and c) minimum temperature (°C).

The Taylor diagram also showed that the simulated datasets perform relatively well in simulating the seasonal pattern for precipitation, minimum temperature and maximum temperature. The gridded datasets perform equally well for precipitation, while WFD performs better than WFDEI regarding minimum and maximum temperatures. Furthermore, WFDEI and WFD showed a very good agreement for their overlapping period (1979-2000).

2.4.2. Hydrological model calibration

The results of model calibration indicated that the model was able to simulate the streamflow quite well for the entire basin (r -.99 to 0.79 and pbias -25.5 to 25.2) (Figure 2-5). The model performed better in the western and southern parts of the basin than it did in the north and northeast. This could be due to the water extraction for agriculture in north and northeast (Iran Ministry of Energy, 2014i) which was not included in this stage.

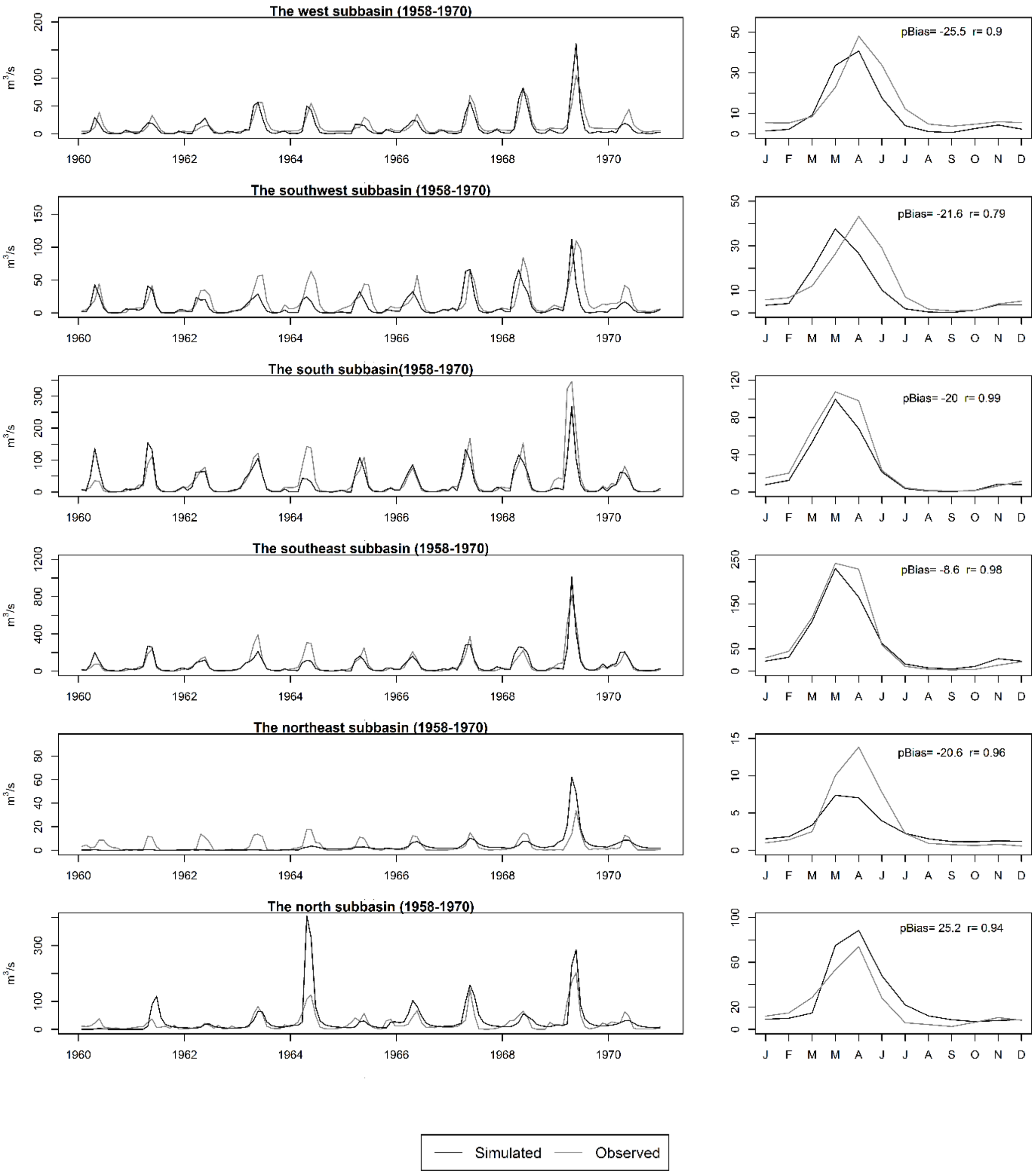


Figure 2-5 Calibration results for monthly time series for 1960–1970 and mean annual cycles of observed and simulated streamflow data for all six subbasins of Urmia basin.

2.4.3. Recent climate change and the impact on inflow

The analysis of mean annual observed precipitation over the basin showed a decreasing trend between 1960 and 2010 from ~390 mm/year to ~330 mm/year over the last 50 years. Precipitation over the basin decreased by 1.12 mmyr^{-1}over the study period (Figure 2-6).

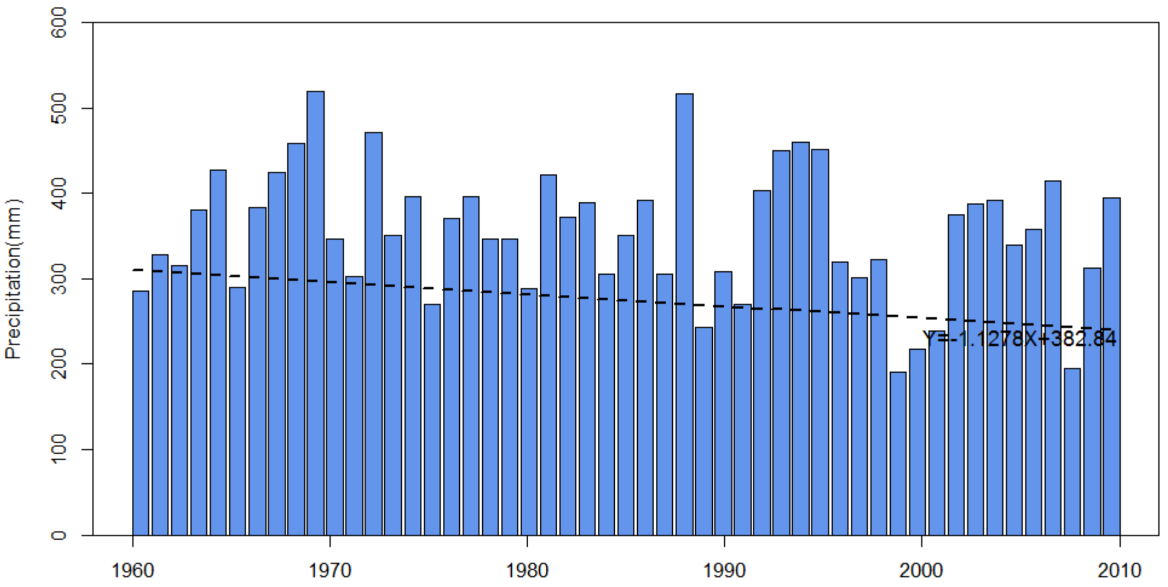


Figure 2-6 Observed mean annual precipitation over the basin obtained from 146 stations (1960-2010), the dashed straight lines indicate related linear regressions.

The naturalized streamflow trend was similar to precipitation, but with the more pronounced decreasing trend and a higher inter-annual variability (Figure 2-7a). The total naturalized inflow into the lake decreased by ~$1.5\times10^9 m^3$ over the last 50 years. The 10-year averages of annual naturalized inflow were higher than EFR for the entire study period (Figure 2-8). However, during the dry period, 1995-2001, the naturalized inflow into the lake was generally less than EFR (Figure 2-7a). In 1999, the inflow reached $1110\times10^6 m^3\ yr^{-1}$, which was the lowest level of the 50-years study period.

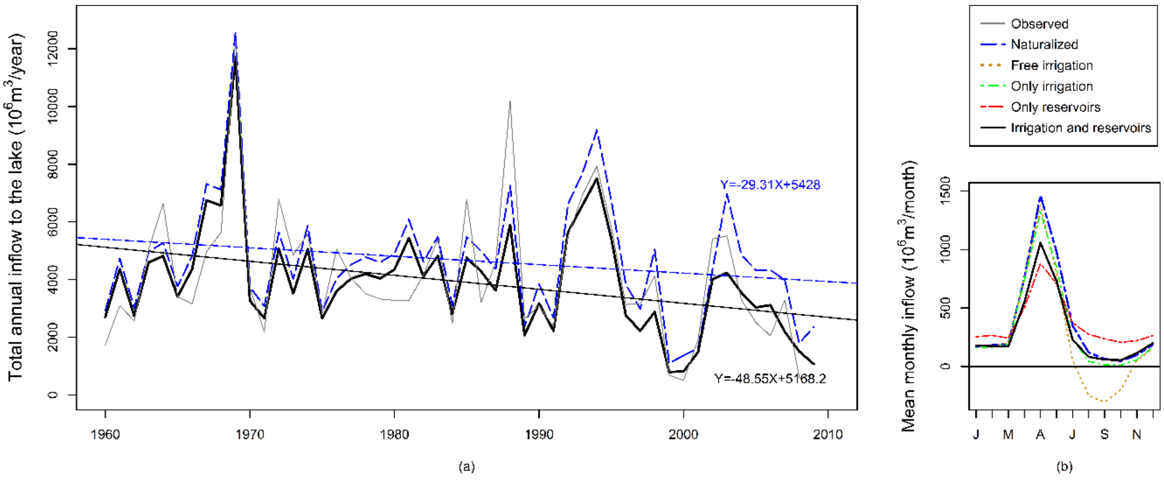


Figure 2-7 a) Simulated and observed total annual inflow into the lake. The inflow was simulated for naturalized conditions and including irrigation and reservoir. The dashed straight lines indicate related linear regressions for naturalized and irrigation and reservoir run. b) The mean monthly inflow, into the lake for naturalized run and runs including only reservoir, only irrigation (limited and free), and combined irrigation and reservoir run.

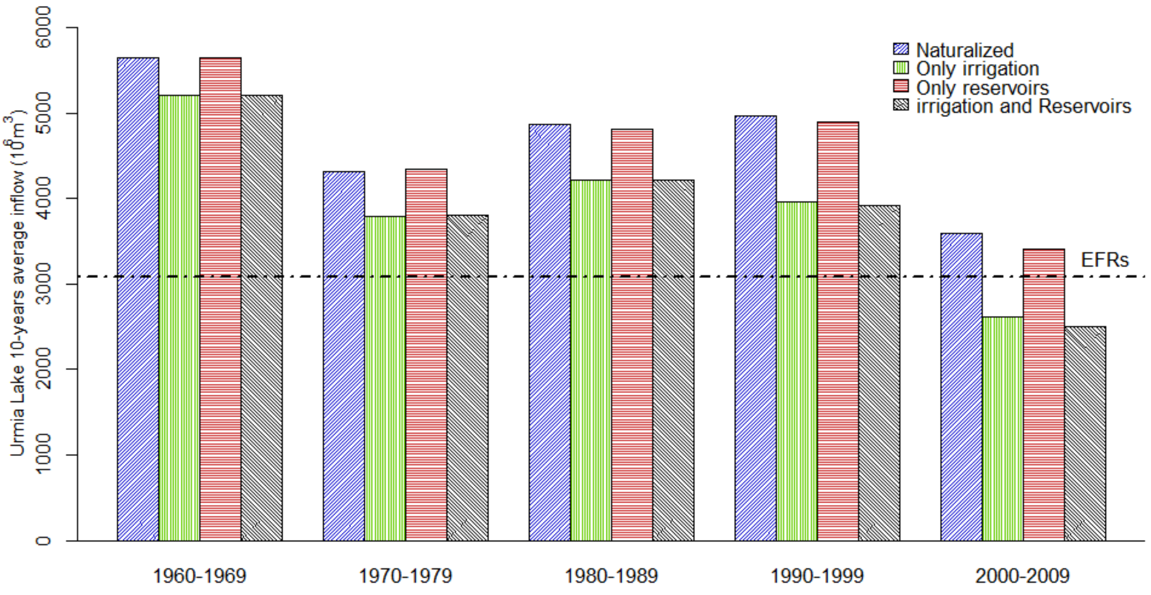


Figure 2-8 The 10-year average inflow to the lake, dash lines represents the Environmental Flow Requirements, $3085\times10^6 m^3$, for Urmia basin calculated by Abbaspour and Nazaridoust (2007).

2.4.4. The impact of reservoir development

To assess how reservoir operation affected the inflow into the lake, we subtracted the reservoir run results from the naturalized run streamflow results (Figure 2-9a). Reservoirs generally stored water in wet years and released it in dry years. This pattern was in balance until ~1995. The negative impacts became slightly visible after a considerable expansion in reservoir capacity in 2004, which can be due to increase in evaporation from the reservoirs surface area. The mean annual amount of evaporation lost from reservoirs increased from $30\times10^6 m^3 yr^{-1}$ to $164.2\times10^6 m^3 yr^{-1}$ over the study period. Although reservoirs did not significantly impact on annual inflow, they increased water availability in dry months in particular (Figure 2-7b). Reservoirs did not have much impact on the 10-year averages of annual inflow (Figure 2-8).

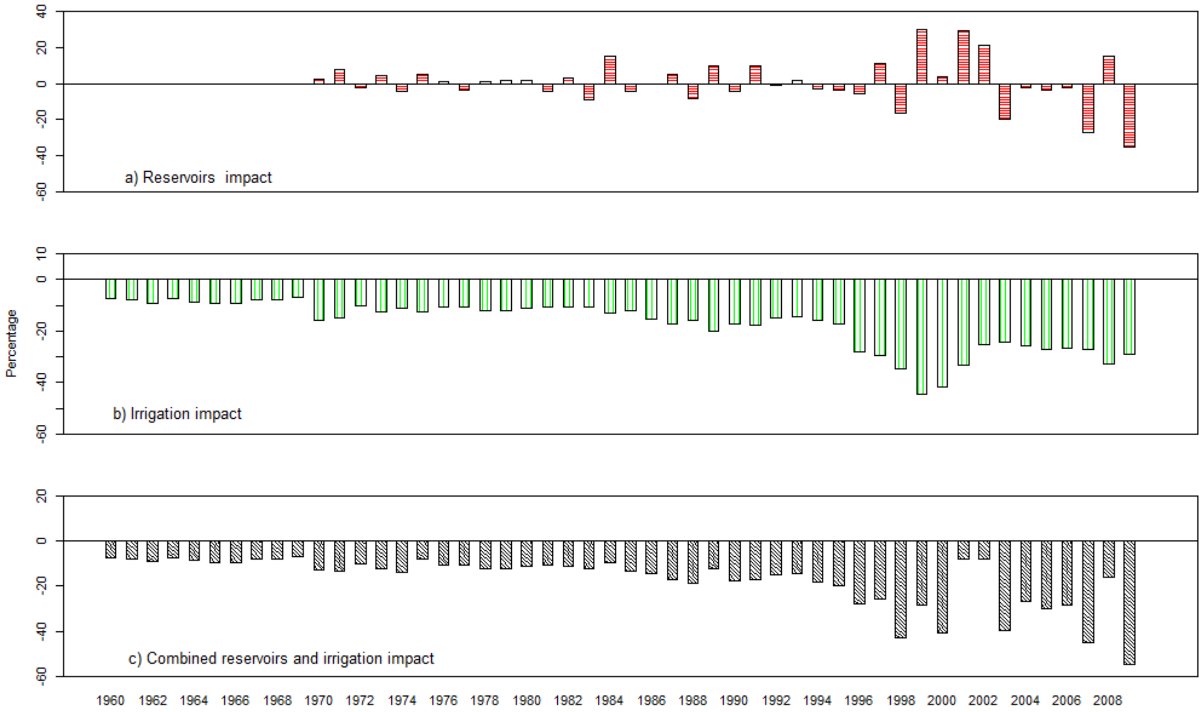


Figure 2-9 The fraction of inflow which compared with the naturalized inflow in the model with a) only reservoir, b) only limited irrigation, c) combined reservoir and irrigation.

2.4.5. The impact of irrigation development

Irrigation always reduced inflow into the lake (Figure 2-9b). In wet years, because more water was available, more of it was used for irrigation. However, the percentage of water taken by irrigation in dry years was higher (Figure 2-9b). Therefore, irrigation increased pressure on the basin's water balance in dry years. During severe dry years, irrigation reduced up to 40% of the inflow into the lake. Furthermore, in the summer time, the basin has a serious shortage in relation to meeting the irrigation water requirements from surface water (Figure 2-7b). The negative values in the free irrigation run (Figure 2-7b) may illustrate a shortage in the supply of irrigation water, meaning pressure on other water resources like groundwater. The average of annual inflow from 2000 to 2010 was less than EFR considering only irrigation (Figure 2-8).

2.4.6. Impacts of water resources development: reservoirs and irrigation combined

The last run included both irrigation and reservoirs, the results of this run agreed quite well with the observed annual inflow into the lake (Figure 2-7a). Irrigation and reservoir development always caused inflow reduction into the lake (Figure 2-9c). However, comparing the 'only irrigation' run with the 'irrigation and reservoirs' run (Figure 2-9b and c) revealed that reservoirs increased inflow in dry years. Developing irrigation and reservoirs combined with the climate change, on average caused 10-year average inflow into the lake to decline from $5202\times10^6 m^3$ to $2502\times10^6 m^3$, a 52% reduction, over the study period (Figure 2-8). It means that the average of annual inflow from 2000 to 2009 was less than EFR considering both irrigation and reservoirs (Figure 2-8). The impact of irrigation and reservoirs is more visible during the last 15 years of the study period (Figure 2-9c).

2.4.7. Relative contributions of climate change and water resources development on the declining lake inflow

The reservoir irrigation run shows that the total average annual inflow reduced by 48% over the whole study period, 1960-2010. To distinguish between climate change and water resources development impacts using the Wang (2014) approach, we identified the start of the altered period. Our analysis shows that the inflow changing point is 1995, which is the starting year of the main irrigation's expansion. Therefore, we selected 1995 as the beginning of the altered period. Based on Equation 1 the total change of inflow (ΔQ) between altered and baseline periods is estimated to be $2735\times10^6 m^3$, for which $1644\times10^6 m^3$ (about three fifth) is attributed to climate change (ΔQ_c) and $1091\times10^6 m^3$ (about two fifth) is attributed to water resources development(ΔQ_h).

We also compared the annual trend in inflow from naturalized run with the trend including irrigation and reservoir run over the whole study period. The results show that average naturalized inflow declined by $29\times10^6 m^2 yr^{-1}$ due to a change in climate (Figure 2-7a). For the simulations including irrigation and reservoirs, the reduction in inflow was $49\times10^6 m^2 yr^{-1}$ showing the changes caused by both climate change and water resources development. This indicates that about three fifth of change (29/49) was caused by climate change over the last 50 years and about two fifth was caused by water resources development. In other words, climate change has caused an inflow reduction of 28% (48%×three fifth) over the study period; while water resources development has caused an inflow reduction of 20% (48%×two fifth).

2.5. Discussion

In order to support water management to protect Urmia Lake from further environmental degradation, it is important to know what has caused the recent shrinkage of the lake. Other studies identified climate change and water resources development as main driving reasons for Urmia Lake desiccation (Farokhnia and Morid, 2014, Fathian et al., 2014, Hashemi, 2011, Hassanzadeh et al., 2012, Jalili et al., 2015, Zeinoddini et al., 2009). By selecting a simulation approach, in this study, we assessed the relative contributions of these driving reasons to the declining inflow. Our assessment included the analysis of precipitation datasets from 146 gauging stations for the period 1960-2010over the basin. This analysis revealed a decreasing trend over the study period which is in an agreement with other studies that assessed the trend of observed precipitation (Delju et al., 2013, Farokhnia and Morid, 2014, Hassanzadeh et al., 2012, Jahanbakhsh-Asl S, 2003, Katiraei PS, 2006, Rezaei Banafsheh M, 2010).

The simulated naturalized river flow trends show a decreasing pattern similar to precipitation. However, the relative decrease in naturalized flows was much higher. This is caused by a relatively low runoff coefficient (Ghashghaei et al., 2013) for the basin. Furthermore, the seasonal and interannual variability of precipitation also have changed significantly over the last two decades (Delju et al., 2013). These longer dry periods can cause more human water extraction. This is also partly why the naturalized inflow declined sharply during the dry period between 1995 and 2001. During this period, flows did not meet EFR, even in the absence of reservoirs and irrigation (simulated). This demonstrates the important role of climate change on the inflow to the lake. This finding is consistent with the trend analysis results of Fathian et al. (2014), who suggested that climate variations in Urmia Lake basin have a direct effect in inferring significant trends in river flow.

Direct evaporation from reservoirs increased considerably over the study period due to increase in total reservoir surface area and probably also due to increases in temperature. However, it did not exceed 5 percent of the inflow into Urmia Lake. Therefore, reservoir operation did only have a limited impact on the average inflow into the lake. Reservoirs can both have positive and negative indirect impacts on inflow. Reservoirs could increase streamflow in dry periods by releasing water stored during wet periods. These results are similar to those found by Adam et al. (2007), who showed little effect of reservoirs on annual trends, but considerable intra-annual changes. They also reported a decreasing trend in winter and early spring. This difference can be attributed to the different climatic conditions at Urmia Lake. On the other hand, as most of the reservoirs were built to supply irrigation projects, the effect of reservoirs should not be assessed in isolation, but rather in combination with the accelerating development of irrigated agriculture in the basin. Due to the sharp increase in water demand for irrigation current reservoirs are increasingly unable to meet increasing demand. In fact, many reservoirs are empty because of declined reservoir inflow. The findings of this study are consistent with the previous study by Fathian et al. (2014), who examined the effect of three large dams in Urmia basin on the inflow. They reported no correlation between the dams operation and annual inflow.

Irrigation had a negative impact on inflow and also on water availability throughout the Urmia Lake basin. Moreover, the combination of irrigation and reservoirs has reduced the inflow into the lake if compared to a situation with irrigation only (without reservoirs). This is explained by additional water being stored in reservoirs for supplying water for irrigated fields. However, for dry years the simulated inflow was higher than the simulated inflow into Urmia Lake including irrigation only (without reservoirs), thus showing the potential role of reservoirs managing water in times of water scarcity.

The average annual inflow dropped by 48% between the years 1960 and 2010. The decreasing trend has been even more pronounced since 1995 when the lake did not receive its EFR during a sequence of years due to a severe drought which was exacerbated by water use for irrigation. To compare and quantify the roles of climate change and human activities on inflow reduction different factors have to be taken into account. Naturalized flow is a function of time, and water resources development is mainly a function of different development stages, so several uncertainties are involved. In this study, we selected two approaches to quantify the distinct role of climate change and water resources development. The first approach was based on assessing the change in inflow before and after substantial human impact. The second one compared the naturalized inflow trend with inflow considering irrigation and reservoirs trend for the whole study period, 1960-2010. Both approaches led to very similar results. Climate change was the main contributor to the inflow reduction (about three fifth) and caused an inflow reduction of 28% over the study period. Shadkam et al. (2016b) assessed the impact of a lowest and highest representative concentration pathways (RCPs) (Moss et al., 2010) on the inflow to Urmia Lake in next century. Their results showed that the effect of climate change is likely to continue in both lowest and highest scenarios. Therefore, the detected trend in this study is likely to belong to a long term change in the climate in this area. Our results also showed that water resources development had a substantial effect on the inflow reduction as well (about two fifth of the reduction, corresponding to 20% of the original annual average inflow, thus representing the remainder of the 48 % drop). Our findings supports other studies that have indicated that a combination of climate change and water resources development have caused the lake degradation (Jalili et al., 2015, Fathian et al., 2014, Farokhnia and Morid, 2014, Hassanzadeh et al., 2012, Zeinoddini et al., 2009). AghaKouchak et al (2015) suggested that human water extraction may be the main reason for the lake shrinkage. However, their results are based on assessing the basin Standardized Precipitation Index; while, the current study results are based on assessing simulated inflow into the lake. Furthermore, another explanation can be difference between satellite-based data, used in their study, and meteorological WFD/EI data, used and validated specifically for Urmia basin in this study, also the length of the data. Furthermore, other studies showed that inflow into Urmia Lake is more sensitive to changes in temperature (Fathian et al., 2014, Farokhnia and Morid, 2014) rather than precipitation which have been used to force the model in the current study any may leaded to the different conclusion. The results of this study confirm the results obtained by Farokhnia (2015) who compared the impact of climate change and human water use on Urmia Lake inflow with three different methods. Their results indicated that climate change was the dominant reason (up to 72%) to reduce the lake inflow.

The models result could be affected by different uncertainties. Firstly, the relatively coarse spatial resolution used for model simulations. Nevertheless, the VIC model was able to simulate the observed streamflow well. It was not possible to develop a forcing data set at a finer resolution for all variables required (precipitation, temperature and wind speed) due to limited availability of observations and the lack of bias corrected forcing datasets other than WFD/EI. However, we included detailed local information about the reservoir characteristics, land use, and irrigation pattern into the reservoir and irrigation modules. As the focus of this study was on the assessment of total annual flows, the resolution uncertainty is expected to be of limited influence on the reliability of our conclusions.

Secondly, the observed data including precipitation, reservoirs storage and irrigation pattern which provided by the Ministry of Energy. However, they are the best available data based on our best knowledge which have been verified by Urmia Lake Restoration Program (ULRP, 2016c). Furthermore, the observed inflow data which were provided by the ULRP from 18 stations located near the outlets of all important tributaries to the Lake. The estimate of the inflow into Urmia Lake might be inaccurate due to two reasons. First, part of the measured flow does may not actually reach the lake (i.e. due to evaporation). Second, direct runoff into the lake and inflow through small seasonal streams has not been accounted for in our estimate.

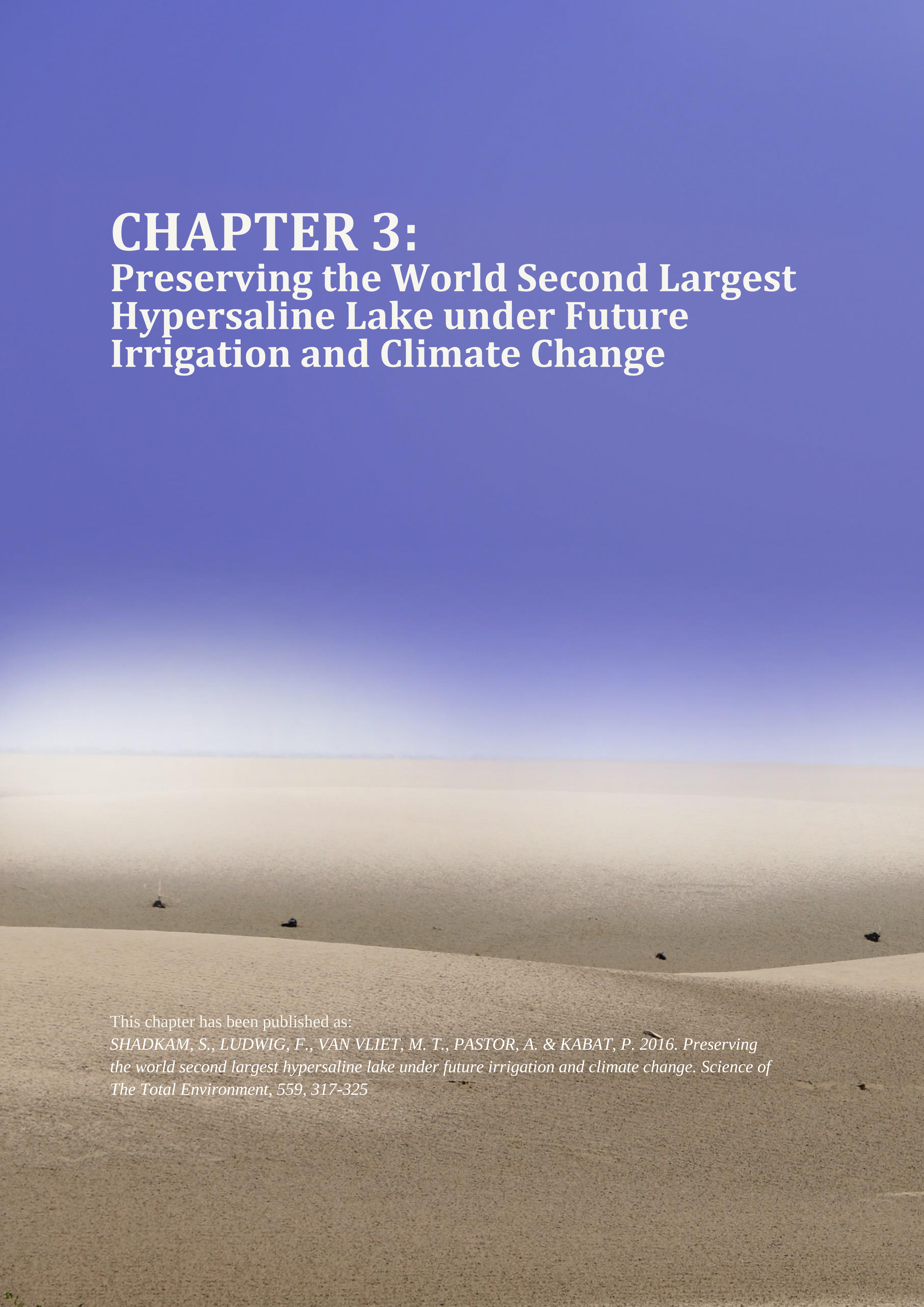
Thirdly, we focused our simulation on the use of surface water although a part of the irrigated water use in the basin originates from groundwater. This might cause the minor differences between observed data and simulated results. The streamflow simulated by the VIC model results from water balance calculations on the land surface including shallow rechargeable groundwater through sub-surface runoff. As a result withdrawal from the shallow renewable groundwater is included in our simulations. However, this is not the case for deep non-renewable groundwater. The simulated availability of water is therefore probably slightly underestimated (Hanasaki et al., 2008). Our results also indicate that currently surface water cannot meet all irrigation water requirements. It is likely; however, that part of the deficit was met by using deep groundwater.

In this study, we compared simulated inflow with used EFR estimated by (Abbaspour and Nazaridoust, 2007), as it has been defined as Urmia Lake Restoration Program target (ULRP, 2016b). The study is based on the assumption that 240 (g/l) NaCl is the threshold that *Atemia urmiuana* can tolerate. However, Agh (2007) reported the negative impact on survival, growth and reproductive of *Artemia urmania* at salinity levels ranging from 75 to 175g/l in a 23-day long experiment. Higher salt concentration was not tested, but analyses of other species of *Artemia* reported no survival above 230 g/l (Browne and Hoopes, 1990). Therefore, an in-depth study to review the Urmia Lake environmental flow requirement is recommended.

It is also recommended that further studies consider the volatile geomorphological situation of the lake. Due to the recent reduction in lake volume, the salinity of the lake water has increased sharply causing about 8 billion tons of salt to fill up the deeper parts of the lake. A recent investigation by ULRP revealed that the depth of the deepest part of the lake changed from 16m to only 2m over the period 1995-2015. Although the drop in water level was only around 7m, a layer of salt of around 7m as well, has filled up the deeper parts of the lake. The ratio of the area to the volume (m^2/m^3) has thus increased considerably, meaning that for the same volume of water much more evaporation is expected.

2.6. Conclusions

Our results show that the recent Urmia Lake degradation was probably caused by reductions in river inflow into the lake due to a combination of changes in the climate and water resources development. Climate change was the main contributor to this inflow reduction. However, water resources development, particularly water use for irrigation, has played a substantial role as well. The results of this study show that urgent action is needed to rehabilitate and preserve the Urmia Lake. This urgent action should include both international action to mitigate climate change impact, and national action to improve water management, in particular to lower the consumptive water use for irrigation. It is also recommended that further studies are conducted for increasing our understanding of environmental flow requirement, the effect of the changing lake geomorphology, and the effect of groundwater extraction, as this can importantly contribute to finding a realistic solution for the Urmia Lake socio-environmental disaster.



CHAPTER 3:

Preserving the World Second Largest Hypersaline Lake under Future Irrigation and Climate Change

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Abstract

Iran Urmia Lake, the world second largest hypersaline lake, has been largely desiccated over the last two decades resulting in socio-environmental consequences similar or even larger than the Aral Sea disaster. To rescue the lake a new water management plan has been proposed, a rapid 40% decline in irrigation water use replacing a former plan which intended to develop reservoirs and irrigation. However, none of these water management plans, which have large socioeconomic impacts, have been assessed under future changes in climate and water availability. By adapting a method of environmental flow requirements (EFRs) for hypersaline lakes, we estimated annually $3.7 \cdot 10^9$ m^3 water is needed to preserve Urmia Lake. Then, the Variable Infiltration Capacity (VIC) hydrological model was forced with bias-corrected climate model outputs for both the lowest (RCP2.6) and highest (RCP8.5) greenhouse-gas concentration scenarios to estimate future water availability and impacts of water management strategies. Results showed a 10% decline in future water availability in the basin under RCP2.6 and 27% under RCP8.5. Our results showed that if future climate change is highly limited (RCP2.6) inflow can be just enough to meet the EFRs by implementing the reduction irrigation plan. However, under more rapid climate change scenario (RCP8.5) reducing irrigation water use will not be enough to save the lake and more drastic measures are needed. Our results showed that future water management plans are not robust under climate change in this region. Therefore, an integrated approach of future land-water use planning and climate change adaptation is therefore needed to improve future water security and to reduce the desiccating of this hypersaline lake.

CHAPTER 3:
Impacts of climate change and water resources development on the declining inflow into Iran's Urmia Lake

3.1. Introduction

To supply food and energy for growing populations, humans have developed reservoirs and extract water for irrigation (Biemans et al., 2011). Furthermore, climate change has a significant impact on the natural hydrological cycle and amplifies water scarcity in (semi)-arid regions (Haddeland et al., 2014, Fernandes et al., 2011, Santos et al., 2014). Consequently, managing water for a growing population without harming natural resources is becoming a serious challenge. In this paper, we assess this challenge in Urmia basin, where the second largest permanent hypersaline lake in the world is drying up (Karbassi et al., 2010).

Urmia Lake, in north-western Iran, is an important internationally recognized natural area designated as a RAMSAR site and UNESCO Biosphere Reserve (Eimanifar and Mohebbi, 2007). It is a home to many species of reptiles, amphibians and mammals along with a unique brine shrimp species (Asem et al., 2012). Urmia Basin supports a variety of agricultural production systems and activities as well as livestock. The basin is located in a politically tensed region bordering both Iraq and Turkey. It is linguistically and culturally diverse area dominated by two ethnic groups, Azeri Turks and Kurdish (Henareh et al., 2014).

Over the last 40 years, the water level and surface area of Urmia lake have declined (Rokni et al., 2015) by 80% (AghaKouchak et al., 2015). As a result, the salinity of the lake has sharply increased which is disturbing the ecosystems, local agriculture and livelihoods, regional health, as well as tourism (UNEP, 2012). Several studies have warned that the future of lake Urmia could become similar to the Aral Sea, which has dried up over the past several decades and severely affected the surrounding people with windblown salt storms (Torabian, 2015). The population around Urmia Lake, however, is much denser compared to the Aral Sea and many more people are at risk (UNEP, 2012). Local reports have indicated that thousands of people around the lake have already abandoned the area (RadioFarda, 2014). It has been estimated that people living within 500 km^2 of the Lake location, are at risk (Torabian, 2015), which could amplify economic, political and ethnic tensions in this already volatile region (Henareh et al., 2014).

Previous studies have indicated that the lake desiccation is probably caused by a combination of human activities and climate change (AghaKouchak et al., 2015, Fathian et al., 2014, Hamzekhani et al., 2015, Hassanzadeh, 2010, Jalili et al., 2015). The area of the agricultural lands has more than tripled over the last 40 years supported by a considerable number of reservoirs and a large irrigation network (Iran Ministry of Energy, 2014i). There has also been a significant decrease in precipitation and an increasing trend in average maximum temperature during the same period (Fathian et al., 2014, Delju et al., 2013). This has caused the most extreme droughts in the basin over the last few decades during the mid-1990s (Tabari et al., 2013). These trends have affected the inflow into the lake (Fathian et al., 2014) which has been recognized as the main reason of the lake shrinkage (Hassanzadeh et al., 2012). Some studies have estimated how much water is needed to restore and protect the ecology, water quality and quantity of the lake (Abbaspour and Nazaridoust, 2007). However, they have not included the important role of climate change which is likely to reduce the precipitation and run-off in both near-term (Kirtman, 2013) and long-term future (Collins, 2013).

To secure enough food and income for a growing population in the basin, the initial government water resources plan intended to increase the irrigated area by 25% supported by additional dams and reservoirs. More recently, a new plan has been proposed aiming to restore and preserve Urmia Lake. This plan proposes to stop all reservoir developments and reduces irrigation water allocation by 40%. However, it is still unclear if the water use reduction plan, which is about to start and has large socioeconomic impacts, is able to restore and preserve the lake under future climate change.

The main objective of this study was to assess the impacts of future water resources management plans under climate change on the water inflow into Urmia Lake during the 21st century. To address this objective we first developed a method to estimate the annual and monthly environmental flow requirement (EFRs) to preserve vulnerable hypersaline lake ecosystems especially in a lack of precise ecological data. By applying the method, we quantified how much water is needed to preserve Urmia Hypersaline Lake. Then, we developed future projections of total inflow into the lake, using the Variable Infiltration Capacity (VIC) hydrological model (Liang et al., 1994), including an irrigation and reservoir module (Haddeland et al., 2006, Haddeland, 2006). The model was forced with statistically bias-corrected General Circulation Models (GCMs) outputs from a low and high representative concentration pathways (RCPs) (Moss et al., 2010). In addition, to study the impact of the water resources plans on the future inflow, the two proposed plans plus the current, and the naturalized (without any irrigation and reservoirs) situations were applied in the model. The simulated inflow was compared with the annual and monthly estimated EFRs to assess the possibilities of Urmia lake restoration and preservation under different climate change and anthropogenic scenarios.

3.2. Study area

Urmia Lake is formed in a natural depression at the lowest point within the closed Urmia basin. The area of the lake has reduced from ~6100 km² in 1995 to ~1500 km^2 in 2014 (Figure 3-1) followed by more than 7m decline in the water level (Figure 2-1). The lake is relatively shallow (maximum depth 16 m) and thus vulnerable to evaporation (Meijer et al., 2012). There are 17 permanent rivers and 12 seasonal rivers which terminate at Urmia Lake. The average inflow into the lake has declined from around 12,000 to $2{,}400 \cdot 10^6$ m^3 over the last four decades (Hamzekhani et al., 2015). The mean annual precipitation is 341 mm $year^{-1}$ which has decreased by 9.2% over the last 40 years (Delju et al., 2013).

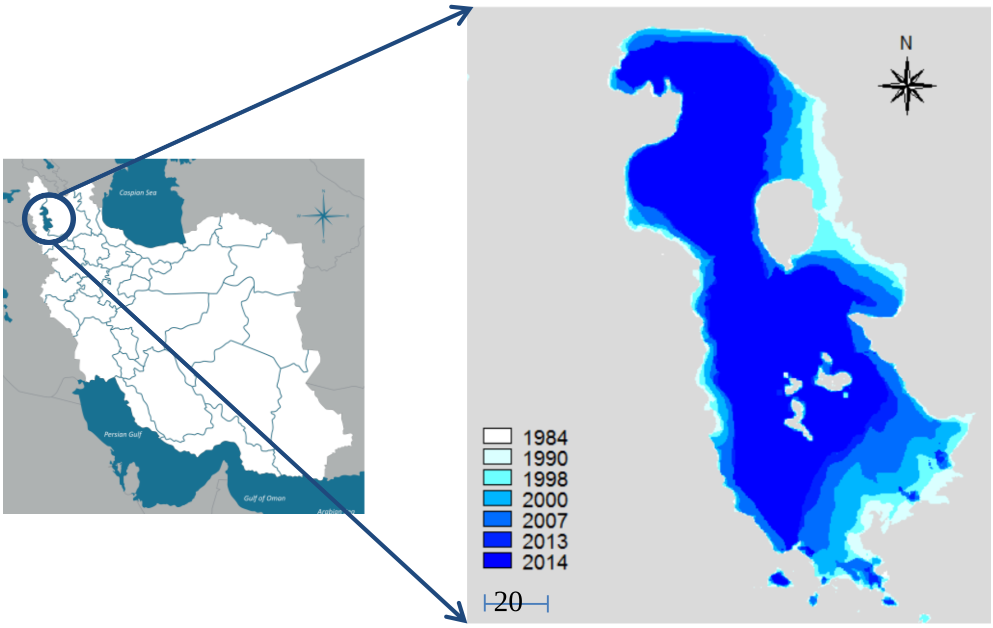


Figure 3-1 Urmia basin location (a) and the surface area changes from 1984 to 2014, derived from LandSat imagery (b) (USGS, 2016).

3.3. Materials and methods

The methodological framework for this study is shown in Figure 3-2. Future scenarios for daily flow into the lake were calculated using the VIC hydrological model forced by bias-corrected outputs from five GCMs, using the representative concentration pathway (RCP) 2.6, lowest; (Van Vuuren et al., 2011) and 8.5, highest; (Riahi et al., 2011), for 2010-2099 and for 1971-2000 (control) in combination with four different anthropogenic scenarios (40 simulations). Historical naturalized inflow from the control period was used to estimate annual and monthly environmental flow requirements (EFRs). To assess the significant impact of water resources plans and the climate change impact, the paired two-tailed Student's t-test was used, P values of < 0.05 were considered significant.

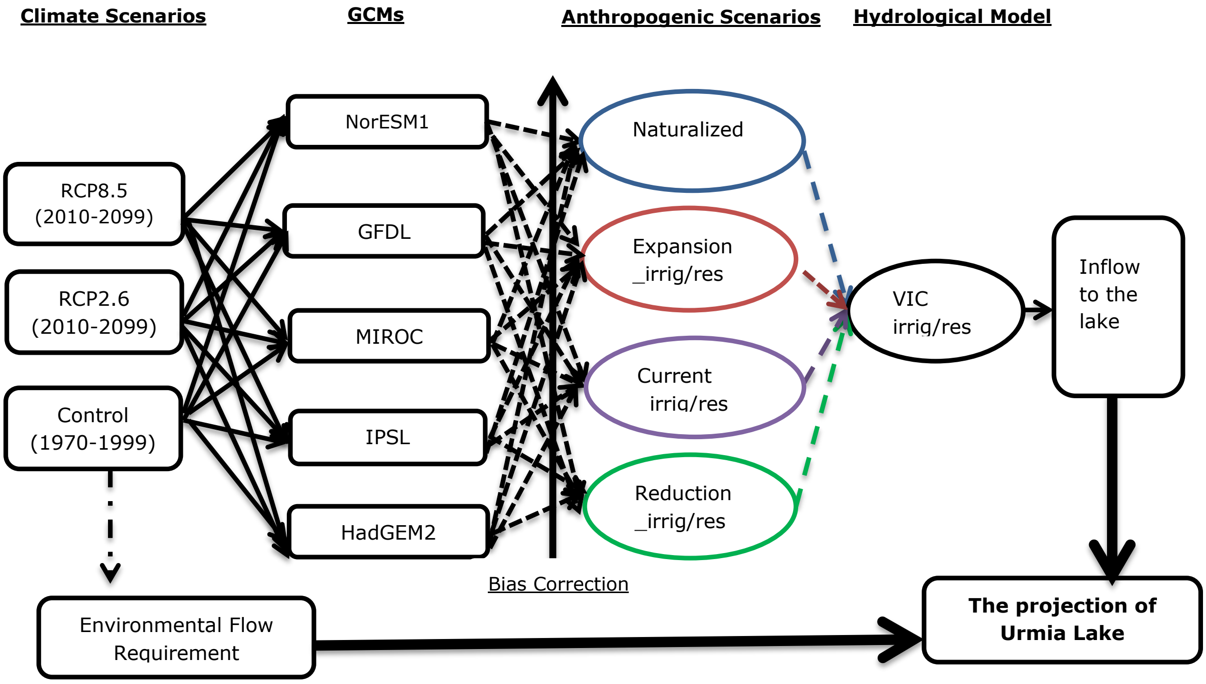


Figure 3-2 Schematic representation of the modelling framework

3.3.1. Hydrological model

The VIC model is a grid-based soil–vegetation–atmosphere transfer schemes model (Liang et al., 1994, Nijssen et al., 2001b, Nijssen et al., 1997). The input data are daily precipitation, maximum and minimum temperature and wind speed. Each grid cell is divided into multiple vegetation types and into multiple soil layers. Evapotranspiration is calculated using the Penman-Monteith equation. The simulated surface streamflow and baseflow, combined referred as inflow in this paper, are routed from each grid cell to the basin as described by Lohmann et al. (Lohmann et al., 1998b, Lohmann et al., 1998a). The VIC model, like most land surface models, does not consider deep groundwater withdrawals (Haddeland et al., 2007), which therefore are not taken into account in this study. The model has been widely used for streamflow studies globally (Nijssen et al., 2001a, Vliet et al., 2013) and for major river basins, as well as for other basins of the world like Europe, the US, and China (Hurkmans et al., 2008, Vliet et al., 2012a, Wu et al., 2007, Xie et al., 2007b). The results of these studies have shown that the model has been able to reproduce the water cycle well.

Haddeland et al. (2006) added reservoirs and irrigation schemes to the VIC model. Therefore, the model simulates irrigation water use, based on the calculated soil moisture deficit. The crop evapotranspiration is first calculated within the grid cells based on FAO’s guideline (Allen et al., 1998b). The grid cells are divided into an irrigated and a non-irrigated area. In the model, irrigation is initiated if soil moisture falls below the transpiration level. To calculate irrigated water demand, an initial model run is performed assuming irrigation water is freely available (free irrigation run). Then, another simulation run is performed where irrigation is limited by water available from the first local river runoff, and, if no runoff water is available, water is extracted from reservoirs (Haddeland et al., 2006). The reservoir scheme calculates optimal release based on simulated reservoir inflow, storage capacity, reservoir evaporation, and downstream water demands. The optimal released calculated based on the SCEM-UA algorithm (Vrugt et al., 2003). The model was able to simulate well the main hydrologic impacts of reservoir operations and irrigation water withdrawals on streamflow in different parts of the world (Haddeland et al., 2006, Haddeland et al., 2014).

Shadkam et al. (2016a) calibrated the VIC model in a manual, systematic way as described by (Xie et al., 2007b), using seven runoff-related model parameters, including the infiltration parameter, and the three soil-layer thicknesses for Urmia basin. They adjusted the model for the Urmia basin by including local information on the elevation, soil, irrigation and reservoir characteristics. They performed a calibration of the model for the basin by dividing the basin to six sub-basins. Results showed that despite the basin's complex topography and semi-arid climate, the VIC-reservoir and irrigation model was able to simulate the streamflow realistically for the all sub-basins.

3.3.2. Environmental flow requirements (EFRs)

Hypersaline lakes, mostly located in semi-arid area, provide a fragile environment which requirements more protection to avoid the extinction of highly adapted species, in dry months in particular (Hammer, 1986, Williams, 2002). Considering that, we selected the Variable Monthly Flow (VMF) method developed by Pastor et al. (2014) which uses algorithms to classify the flow regime into high, intermediate, and low-flow months and takes intra-annual variability into account by allocating EFRs with a percentage of mean monthly flow (MMF). The method increases the protection of river ecosystems during the low-flow season allocating 60% of the MMF to 30% of MMF during the high-flow season. The VMF method showed a better performance compared with other three widely used hydrological methods; Tennant et al. (1976), Smakhtin et al. (2004) and Tessmann (1980), to estimate EFRs for semi-arid river basins around the globe including one of the main river in Urmia basin, Shahr-Chai River (Pastor et al. 2014). However, the VMF method was designed to achieve a "fair" ecological status for river flows which does not take into account the high vulnerabilities of hypersaline lakes. Smakhtin et al. (2006), suggested a threshold of one standard deviation (SD) from the mean value of used variable in EFRs estimation for setting environmental flow targets in order to achieve high ecological protection of critical water resources, especially in the absence of other supporting ecological information. Therefore, we adapted the VMF method and increase the EFRs during all months by one SD of the MMF. For Urmia Lake, the MMF was calculated based on monthly average naturalized inflow for 1971-1990; a time period when the size of the lake was relatively stable (Figure 2-1). Based on this we estimated hypersaline lakes EFRs for different months of the year based on the flow regime according to the equations below:

- *For low flow months (MMF≤40% MAF):*
  EFRs = 60% MMF+SD (MMF)

- *For intermediate flow months (MMF > 40% MAF and MMF ≤ 80% MAF):*
  EFRs = 45 % MMF+SD (MMF)

- *For high flow months(MMF > 80% MAF):*
  EFRs = 30% MMF+SD (MMF)

Where: *EFRs* = Environmental Flow Requirement [m^3s^{-1}]; *MMF* = Mean Monthly Flows [m^3s^{-1}] and *MAF* = Mean Annual Flows [m^3s^{-1}]; *SD (MMF)*= one standard deviation of Mean Monthly Flows [m^3s^{-1}]

3.3.3. Anthropogenic scenarios

In addition to using naturalized flow ('naturalized'), the first scenario, and a continuation of the current water management ('current_irrig/res'), the second scenario, we applied two additional anthropogenic scenarios based on two recent official water management plans. Therefore, the third scenario assumes an expansion of the dams and reservoirs ('expansion_irrig/res') to increase irrigation and food production. The expansion_irrig/res scenario is based on the initial government's plan to develop reservoirs and irrigation in the basin. In this plan, there are around 68 dams and reservoirs in construction or in design phases. The proposed projects that are in a construction phase regulate $1212 \cdot 10^6$ m^3 water and those which are in a design phase regulate $657 \cdot 10^6$ m^3 water. Therefore, total volume of the reservoir will become $3869 \cdot 10^6$ m^3 in nearly 20 years. This will support an additional 130,000 ha. of irrigated land (25% increase). The reservoirs characteristics including height, storage capacity, operating purpose, irrigating area and surface area, were added to the reservoirs scheme of the model. Furthermore, the irrigated lands characteristics including percentage irrigated area, crop characteristics for each cell, and the cropping calendar added to the irrigation scheme (Iran Ministry of Energy, 2014i). The forth scenario aims at restoring the lake and reduces future irrigation ('reduction_irrig'). In April 2014, the steering committee of the Lake Urmia restoration programme announced the approval of a new water resources management plan. In the new plan all reservoirs and irrigation development will be stopped. In addition, the state will buy 40% of irrigation water rights and allocate it to the lake (ULRP, 2014). As it is not clear yet how the plan will be implemented in the basin we evenly decreased 40% of each irrigated cell from the current situation in order to simulate the reduction_irrig scenario.

3.3.4. Climate change scenarios

Bias-corrected daily climate model output as developed within the Inter-Sectoral Impact Model Intercomparison Project (Hempel et al., 2013, ISI-MIP, Warszawski et al., 2014) were used to force the model. Data from five GCMs; (MIROC-ESM-CHEM, IPSL-CM5A-LR, HadGEM2-ES, NorESM1-M and GFDL-ESM2M) were selected based on availability (Taylor et al., 2012). To cover the whole range of future greenhouse gas emissions we selected the highest (8.5) (Riahi et al., 2011) and the lowest (2.6) (Van Vuuren et al., 2011) RCPs. As GCMs output differs significantly from observations, bias-corrected of GCMs output was used to force the VIC hydrological model. Bias-corrections of daily temperature, precipitation, and wind speed were done using quantile mapping (Piani et al., 2010). GCMs projections were simultaneously re-gridded to the 0.5°×0.5° grid of the Climatic Research Unit of the University of East Anglia (CRU) and bias-corrected to the reference data set of WATCH Forcing Data (WFD) (Weedon, 2011) for the period 1960–1999.

3.4. Results

3.4.1. Evaluation of control simulation of river discharge

Simulated inflows for control period 1971-2000 of five GCMs were compared with those based on the historical WFD also with observed values to evaluate the overall performance of the VIC-irrigation and reservoir model (Figure 3-3). Boxplots for simulated mean annual inflows based on the five GCMs corresponded well with boxplots of the observed values (Figure 3-3). However, the median values are slightly overestimated for MIROC and GFDL and underestimated for HadGEM2 and IPSL compared to observations. The median results derived from NorESM1 were quite similar as the observed inflow. Furthermore, the boxplots of simulated discharge for all GCMs correspond closely with the boxplots for WFD, which indicates that there is no distinct impacts of biases in GCMs output on the control inflow simulation.

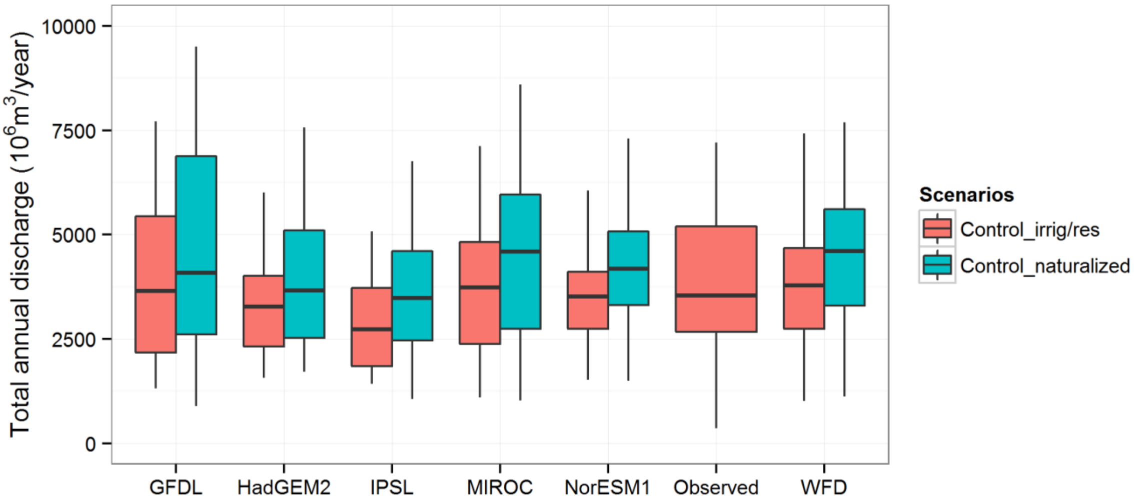


Figure 3-3 Boxplot of simulated annual inflow for five GCMs and WFD compared with observed values for control period (1971-2000). The boxes illustrate the 25th, 50th, and 75th percentiles of the ensemble. The whiskers represent the total sample spread.

3.4.2. Climate change impacts

Simulations results showed that climate change is reducing the inflows into the lake during the high flow season, especially in April and June (Figure 3-4). This is the case for both RCP2.6 and 8.5. However, the decrease in inflow is much higher under RCP 8.5. By mid-century (2040-2069) the mean and peak of the annual cycle of projected naturalized inflow under RCP2.6 is reduced by 10% and 15%, respectively. These values are 27% and 38% for RCP8.5, respectively. In winter (low flow season) the inflow will slightly increase. In addition, the mean annual cycles show two weeks delay in the peak flow for RCP2.6 and one week for RCP8.5. Figure 3-5 shows that the mean annual naturalized inflow into the lake will be reduced by 13% for RCP2.6 and 37% for RCP8.5 by the end of the century. Unlike RCP2.6, the reduction in naturalized inflow under RCP8.5 will be significant in early, mid and late century compared to the historical inflow.

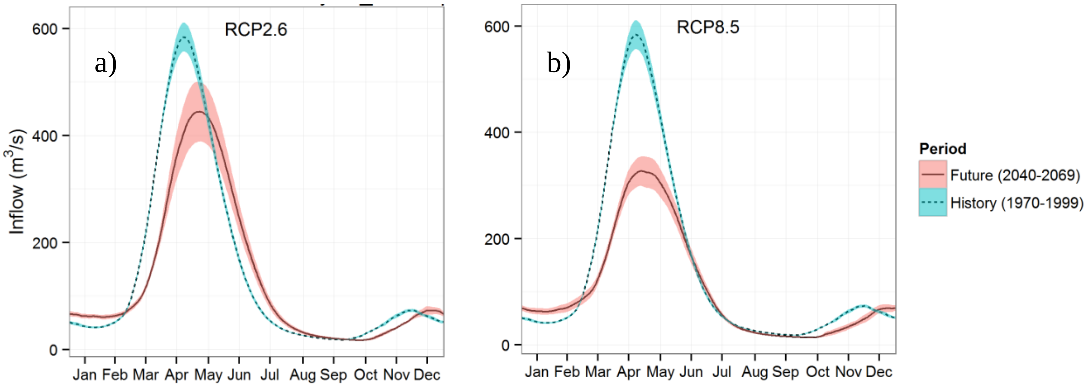


Figure 3-4 mean annual cycle of projected 30-day moving average of inflow for five GCMs for control period (1971-2000) and future (2040-2069) under RCP2.6 (left) and RCP8.5 (right). The shadows represent the standard error of the mean for all five GCMs.

3.4.3. Impacts of anthropogenic scenarios

The results from the control period (1971-2000) showed that the reduction_irrig scenario would have resulted in a 13% increase in inflow compared to current-irrig/res scenario. While, the expansion_irrig/res scenario would have decreased the inflow by 10% compared to the current-irrig/res scenario (Figure 3-5). The results for future climatic conditions showed that the expansion_irrig/res will have a considerable impact on the inflow reduction in the coming century. By the end of the century, the expansion_irrig/res scenario will cause a significant decline in the thirty years mean inflow compared to current_irrig/res by 10% under RCP 2.6 and 12% under RCP8.5. On the other hand, the reduction_irrig scenario will increase the inflow in next century compared to other water use scenarios. Under RCP2.6, the reducing irrigation scenario will increase significantly the thirty years mean inflow compared to the current_irrig/res by 11% by the end of the century. For RCP8.5 this value is 10%. The reduction_irrig scenario will have a significant impact on inflow under RCP2.6 and not under Rep8.5; while expation_irrig/res will have a significant impact in both RCPs. The uncertainty range increases over time for both RCPs.

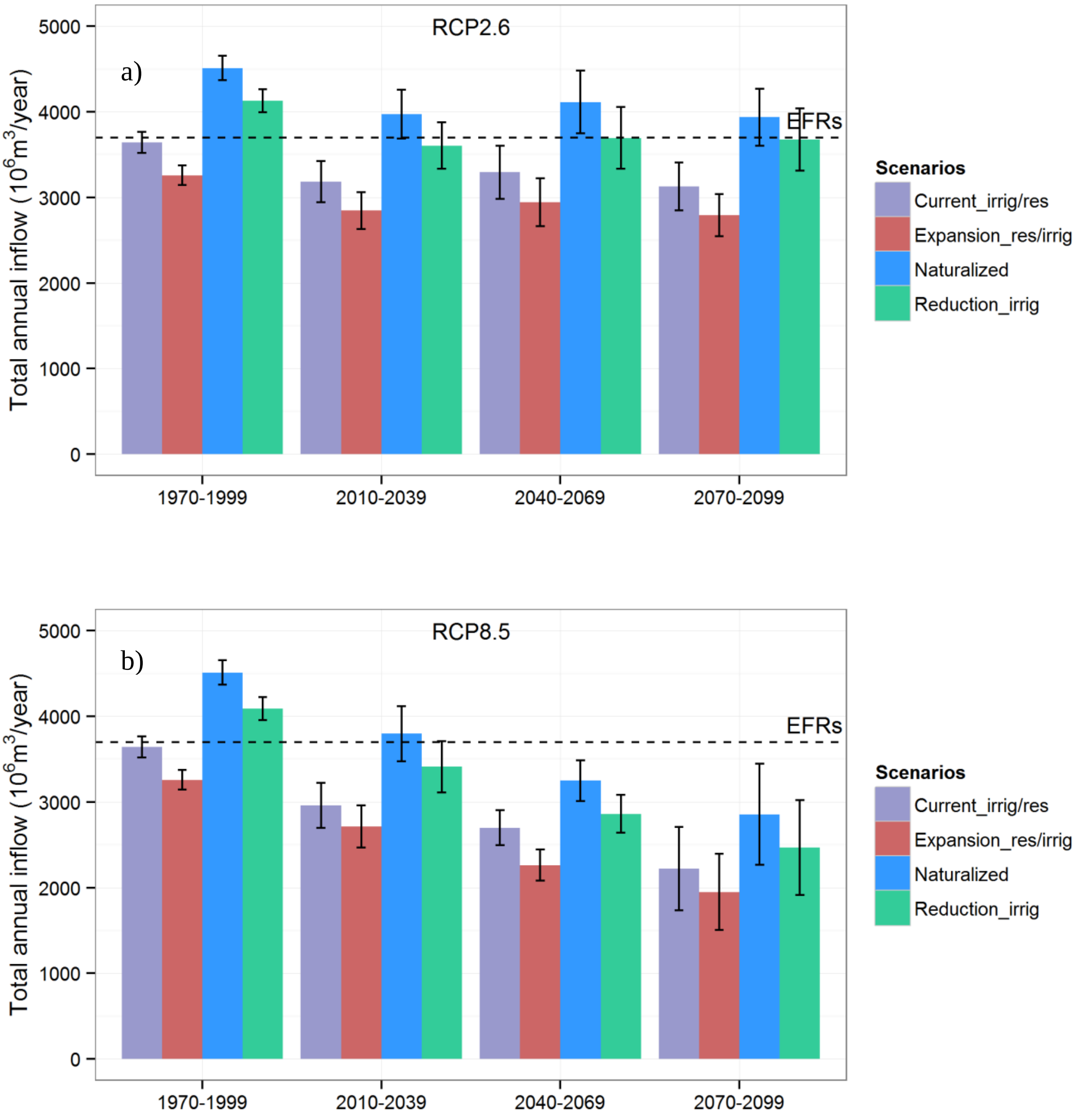


Figure 3-5: Total average inflow to that lake for the control (1971-2000) and future time slices (2010-2039, 2040-2069 and 2070-2099), for the two different water resources plans under RCP 2.6 (a) and RCP 8.5 (b), compared with EFRs, the error bars represent the standard error of the mean.

3.4.4. Fulfilling environmental flow requirements (EFRs)

The estimated annual and monthly EFRs based on the adopted VMF method are presented in Figure 3-6. The calculated annual EFRs estimated to be around 3.7·10^9 m^3. Simulation results indicated that for the control period the EFRs would have met for all scenarios except expation_irrig/res.

Under RCP2.6, the naturalized and the reduction-irrig scenarios inflows on average resulted in sufficient flows to sustain EFRs. However, this was not the case for current_irrig/res and expansion_irrig/res scenarios where the deficit will be around 15%, 24% by end-century, respectively. Under RCP8.5, all water use scenarios will result in inflow well below the EFRs in the whole century. The deficit would be 23%, 33%, 39% and 47% for naturalized, reduction_irrig, current_irrig/res and expansion_irrig/res scenarios by the end of the century, respectively.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
EFRs(×$10^6$$m^3$)	204	181	257	534	1108	611	270	115	62	42	128	185	3700

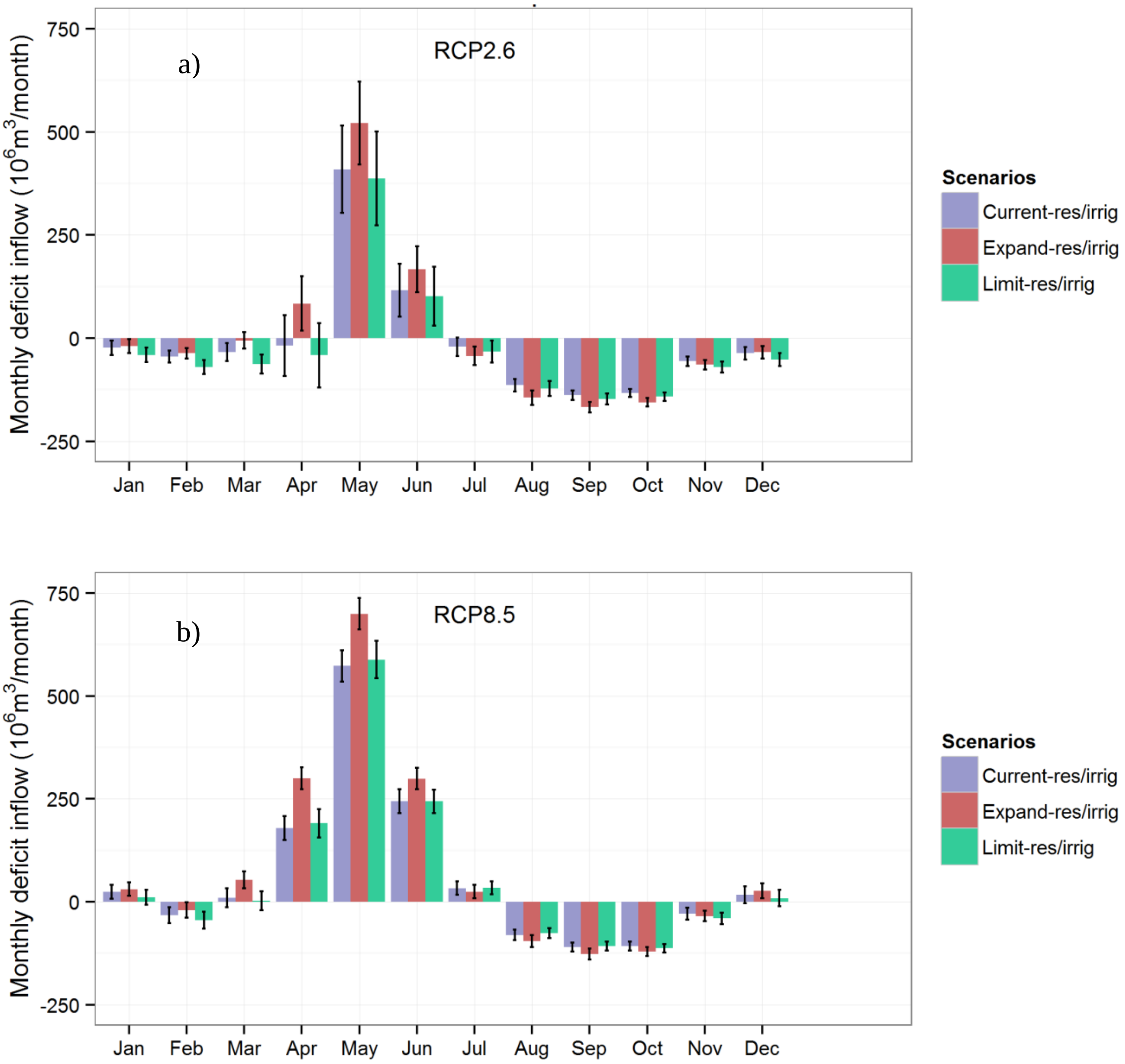


Figure 3-6 The monthly environmental flow requirements (EFRs) (table) and the monthly average of projected inflow for mid-century (2041-2070) deficit for different water resources plan under RCP 2.6 (a) and RCP 8.5 (b), the error bars represent the standard error of the mean.

Figure 3-6 shows the monthly predicted EFR deficit for the lake for mid-century (2040-2069). Regardless the climate and water management scenarios, the lake will be in the highest deficit from April to June. From July to November the lake will meet the EFRs, but small inflow deficits are projected for December- March. Overall, the EFR deficits are stronger for RCP8.5 than RCP2.6.

3.5. Discussion

3.5.1. Impact of uncertainties in modelling framework

Our modelling results are affected by different uncertainties related to the climate forcing and model application. First of all, due to significant biases in GCM data, we used bias-corrected climate forcing data as input to the VIC hydrological model. The statistics for simulated discharge for the control simulations of the GCMs generally correspond well with the simulations based on the WFD dataset and observed discharge values. This showed that the bias-correction method was successful in eliminating the main bias. Haddeland et al. (2014) used the same data set of bias-corrected GCMs output to force the same model (VIC-irrigation and reservoir model) and their results correspond well with the control period. To include uncertainties in future climate forcing data, in particularly regarding future precipitation, we used five different GCMs. Although these climate models differed in the projected changes most models indicated a clear drying trend. However, the use of a larger number of GCMs outputs would better represent the structural uncertainty in climate models (Tebaldi and Knutti, 2007).

Secondly, the coarse spatial resolution of the simulation contributes uncertainties in the results. It was not possible to develop a forcing data set at a finer resolution for all required forcing variables (precipitation, minimum and maximum temperature and wind speed) due to limited availability of observations. However, (Shadkam et al., 2016a) included more detailed local information of elevation, soil, land use, irrigation patterns and reservoirs of Urmai’s basin during calibration and this improved the quality of simulated total inflow which showed a good match with the observed values.

In addition, our study focused on the use of surface water although a part of the irrigated water use in the basin originates from groundwater. Model simulations did not explicitly include groundwater and this could affect our results. However, the simulated streamflow in VIC model is the result of water balance calculations on land surfaces, which includes also the shallow rechargeable groundwater through base flow. Therefore, withdrawal from the shallow groundwater below the recharge rate is implicitly included in the simulations. Nevertheless, this does not apply to deep non-renewable groundwater (Hanasaki et al., 2008). In Urmia basin, the total groundwater extraction (all sectors) was estimated to be around $2100 \cdot 10^6 m^3 yr^{-1}$ (ULRP, 2016a). Around $1000 \cdot 10^6 m^3 yr^{-1}$ of this amount is extracted from shallow groundwater and Qanats, which is partially included in the simulation. The rest, $1100 \cdot 10^6 m^3 yr^{-1}$ comes from deep groundwater. However, almost half of groundwater extractions in Urmia basin are illegal (ULRP, 2016a). This over-exploitation of the basin groundwater has resulted in critical drops in groundwater levels within the basin. To address this problem, illegal water withdrawals from groundwater has been strictly banned in by the government in this region (ULRP, 2016b). This indicated that groundwater extraction is likely to decrease in the near future and the groundwater uncertainty is therefore probably smaller. However, it is recommended that future studies assess the role of groundwater extraction on the lake hydrology.

3.5.2. Evaluation of environmental flow requirements

To assess whether future water resources management plans allocate enough water to preserve the lake ecosystem, we first needed to define minimum environmental flow requirements (EFRs) for this hypersaline lake. The selection of EFRs method is a crucial step in the methodology of this study. Most ecological-based EFRs methods focus on the vulnerability of the lake but ignore the extra protection during dry months. It may cause underestimations in the result. By selecting a hydrological approach and classifying flow regimes, we were able to increase the protection for low-flow months by allocating more flow. We estimated the annual EFRs to be about $3.7 \cdot 10^9$ m^3 which is a little bit higher than the average inflow over the control period (1971-2000). Considering that Urmia Lake has started to shrink around 1995, this result was expected and confirmed the ERFs estimation in the current study. Our EFRs estimation is higher than a previous study by Abbaspour and Nazaridoust (2007) who estimated ecological EFRs to be $3.08 \cdot 10^9$ m^3. Their EFRs estimation was based on calculating inflow applying the difference between the direct evaporation and precipitation (E-P) on their estimated ecological lake surface ($4.6 \cdot 10^9$ m^2). However, the lake (E-P) has increased in the last few years which would increase their environmental flow estimations. In addition, we allocated higher flows for EFRs for dry months to increase the protection of the lake, which can also be the reason of higher estimation of EFRs in this study.

3.5.3. Historical assessment

Our results from the control period (1971-2000) indicated that without climate change, the inflow would have been sufficient to meet the lake EFRs for all water resources scenarios expect expand_irrig/res. Salt lakes, hypersaline lakes in particular, are so sensitive to any minor changes in any component of their hydrological budgets (Williams, 2002). Therefore, it is not surprising that the lake responses quickly to any changes in climate. The results also showed that the anthropogenic scenarios could have had a considerable role to play on the historical inflow so that the inflow under naturalized and reduction_irrig scenarios were estimated considerably higher than EFRs. The finding of the current study supports other studies that indicated the combination effect of climate variabilities and change and water resources management plans on the lake degradation. Hassanzadeh et al. (2012) showed that changes in inflows due to the climate change and water resources management plan caused 65% of the lake desiccation. Furthermore, Fathian et al. (2014) found a correlation between climate variabilities (precipitation and temperature) and the inflow reduction. Jalili et al. (2012) also reported a significant correlation between the lake level climate variability indices and anthropogenic drivers.

3.5.4. Evaluation of future scenarios on the lake inflow

The results clearly showed the significant impact of climate change on annual inflow to the lake under RCP8.5. This impact was not significant under RCP2.6 (Figure 3-5). These results are consistent with the IPCC report which showed a decline in runoff for this region for both near-term (Kirtman, 2013) and long-term future (Collins, 2013) under the strong greenhouse-gas concentration scenarios. These findings are also consistent with the results obtained by Asokan et al. (2016) for Aral Sea basin, which has quite similar condition as Urmia basin (Torabian, 2015). They investigated the freshwater fluxes and their changes provided as output from 22 CMIP5 models under RCP2.6 and RCP8.5. They showed that most GCMs projected a decline in runoff in the Aral Sea basin, with overall negative values of runoff. However, they reported higher range of uncertainties in future runoff compared to our study, which could be partly related to the larger ensemble of GCMs used in their study.

Seasonal changes in water availability should be considered in the development of adaptation and improved water management strategies. Our results showed that under both RCPs, climate change will reduce the water availability in the basin especially in the wet season. This is an important result as the basin already has a serious challenge to secure water availability. IPCC also reported a projected decline in future precipitation for the same period (March till August) for this region (Kirtman, 2013). A reduction in seasonal runoff with a shift in peak flow under both RCP 2.6 and RCP 8.5 was also reported for the Aral Sea basin (Asokan et al., 2016).

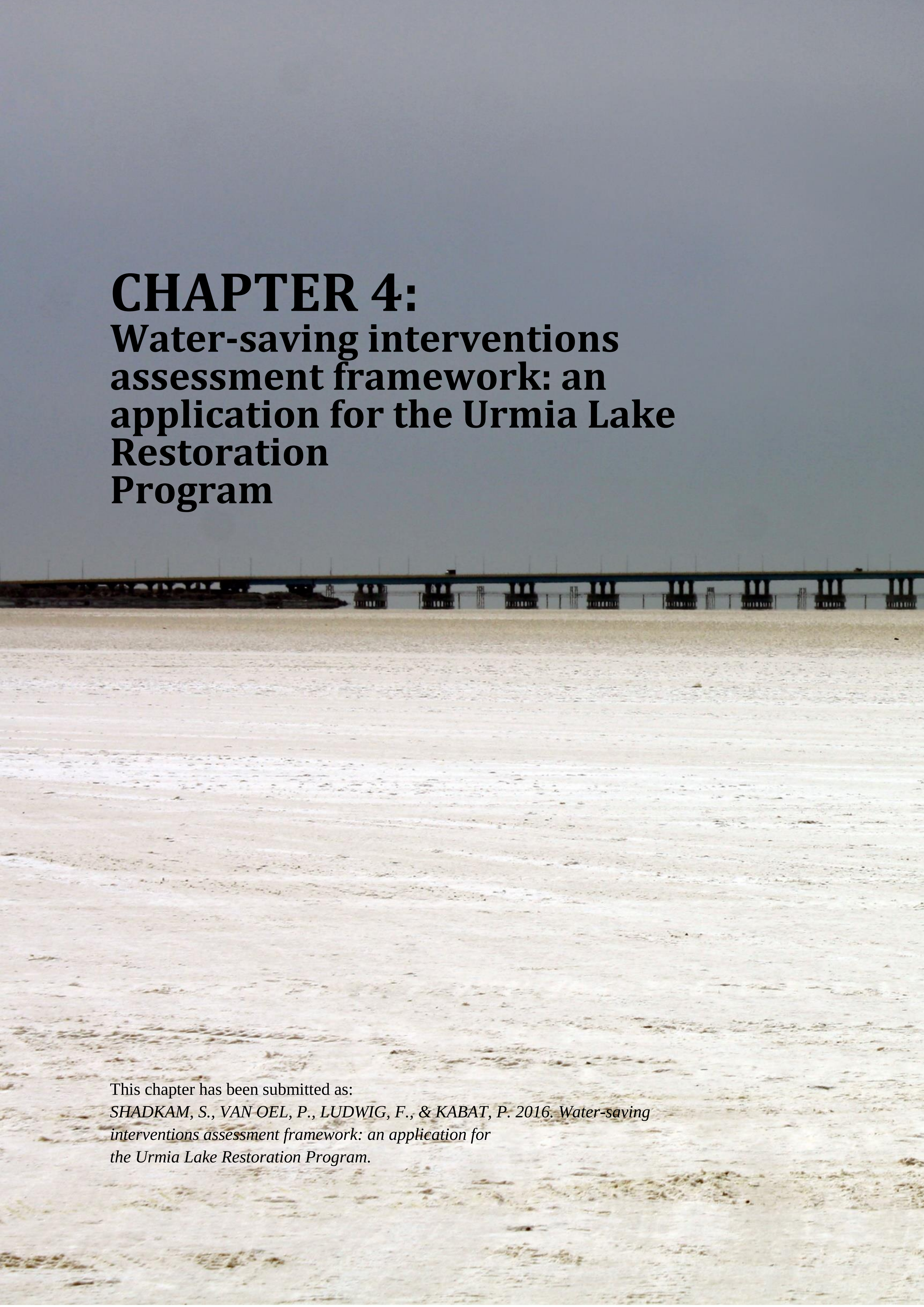
3.5.5. Future of the lake and possible adaption options

Our results indicated that if future climate change is limited due to rapid mitigation measures (RCP2.6) inflow can just meet the EFRs for the limited irrigation management plan. In this case implementing the limited irrigation plan should be the first priority. However, this is not the case for the high concentration scenario also other water resources plans. Under more rapid climate change scenarios (RCP8.5) limited irrigation might be effective in short-term, but would be insufficient in the long-term, so more drastic measures are needed. In general, the impacts of different water resources strategies were more visible under the low concentration scenario (RCP2.6) than under the high concentration scenario (RCP8.5), showing that the dominant impact of climate change mitigation in this scenario. O'Reilly et al. (2015) assessed 325 lakes temperature in 25 years using worldwide synthesis of in situ and satellite-derived data. The results showed that lake warming rates are dependent on combinations of climate and local characteristics. They showed that most lakes are warming and Urmia Lake is among the lakes with the warming rate higher than global average. They asked the urgent adaption efforts for the warming lakes (O'Reilly et al., 2015).

To restore Urmia Lake various adaptation strategies have been explored. First, a considerable amount of water should be transferred to the lake to restore the lost water volume. Urmia Lake Restoration Program (ULRP) announced that 12m3·109 water would be needed to rescue the lake (ISNA, 2016). This amount of water is much more than available water inside of the basin. A few possible new water sources have been proposed including the Zaab River, the Aras River and the Caspian Sea (ULRP, 2016a). However, diverting water from neighbouring basins has its own challenges as both the Zaab and Aras are transboundary basins (Golabian, 2011). In addition, there is no possibility to transfer more than 600 and 140 ·106 m3 of water from Zaab and Aras annually (ULRP, 2016b), respectively, which are much less than required water for the lake restoration. Water transfer from the Caspian Sea would be very expensive and time consuming regarding a long distance and much higher elevation of Urmia Lake (ULRP, 2016b). Another idea is transferring treated wastewater to lake (ULRP, 2014). However, as currently the basin wastewater mostly joins groundwater, this plan might put more pressure on the groundwater. Furthermore, the highest EFRs deficit will be from April to June. Therefore an integrated water management plan, emphasizing seasonal water management, could play a role in sustaining the lake. Decreasing irrigation water demand by changing the crops and water reuse and recycling can also contribute; however it probably is not sufficient to fully restore the lake. Therefore, a feasible solution might be to restore the lake partially by reducing the surface area of the lake till more water available. This could be done by diverting the flow to the deep part of the lake and/or by launching “embayments” in the lake next to inflowing rivers (UNDP, 2014). A phased plan should be developed, which should be updated in each stage regarding the climate change trend and water availability. Since already 80% of the lake has been desiccated (AghaKouchak et al., 2015), it is possible that the lake will dry up completely in case of rapid global warming. Therefore it is recommended to assess also an adaptation plan in case of complete drying of the lake in the near future.

3.6. Conclusions

In this study, we assessed how water resources plans can fulfil Urmia lake inflow requirements under different climate change scenarios. The results showed that the water resources plans are not robust to changes in climate. In other words, if future climate change is limited due to rapid mitigation measures (RCP2.6) the new strategy of reduction of irrigation water use can contribute to preserve Urmia Lake. However, this water management strategy is insufficient to preserve the lake under higher climate scenario (RCP8.5). Therefore, regarding a drier future and increasing water demand in the region, an urgent action on both regional (to limit anthropogenic impact) and global scale (to limit greenhouse-gas concentration) is needed to restore the lake. The results of this study highlight the need to incorporate climate change impact to adaption efforts for desiccating saline and hypersaline waterbodies, as one the most earth's vulnerable ecosystem, under future development and climate change.



CHAPTER 4:

Water-saving interventions assessment framework: an application for the Urmia Lake Restoration Program

This chapter has been submitted as:
SHADKAM, S., VAN OEL, P., LUDWIG, F., & KABAT, P. 2016. Water-saving interventions assessment framework: an application for the Urmia Lake Restoration Program.

Abstract

Increases in water demand often result in unsustainable water use, leaving insufficient amounts of water for sustaining natural environments. To spare water for natural resources, water-saving interventions have been introduced to the environmental policy agenda in many (semi)-arid regions. As many such policies have failed to reach their objectives of increasing water availability for the environment, a comprehensive tool is needed to assess them. We introduce a constructive policy-assessment framework that estimates five components: i) total water demand under socioeconomic scenarios; ii) water supply under climate change scenarios; iii) water withdrawal for different sectors; iv) water depletion; and v) environmental flow. The framework was applied to assess the Urmia Lake Restoration Program (ULRP), which aims to restore the drying Urmia Lake in north-western Iran by increasing lake inflow by $3.1\times10^{6}m^{3}yr^{-1}$. Results suggest that although the ULRP helps to increase inflow by up to 57%, it is unlikely to reach its target. The analysis shows that there are three main reasons for this potentially poor performance. These are: i) decreasing return flows due to increasing irrigation efficiency, meaning that the expected increase in lake inflow volume is smaller than the volume saved by increasing irrigation efficiency; ii) increased depletion, because the fact that agricultural water demand is currently higher than available water for agriculture has been overlooked and, as a result, increased water use efficiency may result in increased water depletion; iii) the potential impact of climate change, which could decrease future water availability by 3–15%, has been ignored. Our analysis suggests that to reach the intervention target, measures need to focus on reducing water demand and water depletion rather than on reducing water withdrawals. The assessment framework can be used to comprehensively assess water-saving intervention plans, particularly in water-stressed basins

CHAPTER 4:

Water-saving interventions assessment framework: an application for the Urmia Lake Restoration Program

4.1. Introduction

During the last century, water management policies mainly focused on developing water resources to secure food and energy for a growing population. This led to an increasing number of reservoirs, wells, and irrigated areas (Sterling et al., 2013). Climate change has also had a significant impact on water scarcity in (semi)-arid regions (IPCC, 2014b). Water demand has thus approached, or is approaching, the limit of water availability in many basins, also referred to as basin closure (Molle et al., 2010). This leaves limited volumes of water available for the natural environment (Karimi et al., 2013a). The Colorado River in the United States, for instance, no longer reaches the Gulf of California (Getches, 2014), the Aral Sea has desiccated due to a decline in inflows from the Amu Darya and Sir Darya rivers (Micklin, 2007), and Bolivia's second largest lake, Lake Poopó, has already dried up (Seiler et al., 2013). To prevent further environmental degradation and to promote resilience to drought, water-saving interventions (solutions) have been introduced to the environmental policy agenda in many (semi)-arid regions (Wada et al., 2014). However, many of these policies have not only failed to reach their goal of saving water for the environment, but have also weakened basin resilience through loss of flexibility and redundancy (Scott et al., 2014). Water-saving policies in southern Spain, for instance, have increased (rather than decreased) water depletion by 20%, along with a fourfold increase in costs of management and operation (Rodríguez-Díaz et al., 2011). This calls for a better understanding of the complex impacts of water-saving interventions on the water balance of basins.

The key to understanding a water-saving policy is to distinguish between water withdrawal and water depletion. Water withdrawal refers to the total amount of water extracted from a basin for different uses; water depletion is the fraction of water withdrawal not returning to the water system. Many efforts to improve water-use efficiency, especially in agriculture, focus on reducing withdrawals with sometimes little impact on water depletion. Without a clear distinction between withdrawal and depletion, misconceptions and misinterpretations of performance indicators for water-saving policies can occur (Perry, 2007). The term "water-use reduction" may thus be interpreted either as reduction of "water withdrawals," or as "water depletion." Furthermore, it is important to distinguish between controlling water demand and water withdrawal, as these are associated with different management options and regulation (Karimi, 2014).

It is also important to undertake a basin-wide approach when it comes to increasing water-use efficiency (Lankford, 2013). Increased efficiency in resource use can lead to increased total resource use (Batchelor et al., 2014). This is known as the rebound effect and has been reported in many water-saving investments (Gómez and Pérez-Blanco, 2014, Qureshi et al., 2010, Peterson and Ding, 2005, Contor and Taylor, 2013, Soto-García et al., 2013). Promoting irrigation efficiency often not only reduces withdrawals, but also decreases return flows. Changes in return flows link field hydrology to basin hydrology (Arumí et al., 2009, Dor et al., 2011, Nasri et al., 2015, De Graaf et al., 2014). If surface irrigation systems are replaced by sprinkler or drip systems, the return flow decreases, which in turn reduces downstream water availability (Scott et al., 2014, Lankford, 2012) and can amount to up to 60% (77% in rice fields) of the water applied for irrigation (De Graaf et al., 2014). Cai et al. (2001) used an integrated modelling approach, which included hydrologic and agronomic models for evaluation of basin management scenarios in the Maipo River Basin in Chile. They showed that increased irrigation efficiency in agricultural areas can negatively affect river flow, as water depletion increases even if water withdrawals decline.

Existing water policies often ignore possible changes in future water availability and demand. In (semi)-arid regions rainfall is often unpredictable, and there are large annual and seasonal differences in terms of water availability. This variability may further increase, and in many semi-arid regions water availability is projected to decrease due to climate change (Vörösmarty et al., 2010). Moreover, water demand, especially for irrigation, often increases in these areas and will become even more pronounced with increasing global warming (Haddeland et al., 2014). Water demand is also likely to increase in the domestic and industrial sectors due to population growth, socioeconomic development, and land use change (Foley et al., 2011).

Although quite well-described in the literature, the dynamic effect of these complexities is not always adequately addressed in water-saving policies. In the absence of an adequate basin-wide assessment tool, water-saving policies may even aggravate water scarcity and put more pressure on natural resources (Scott et al., 2014, Törnqvist and Jarsjö, 2012, Gleick et al., 2011). Therefore, in this study we introduce a comprehensive framework for assessing water-saving interventions. The framework depicts real water saving by distinguishing between water withdrawals, depletion, and demand in the context of uncertainties in future demand and supply. To demonstrate the water-saving intervention assessment framework, we applied it to evaluating proposed water-saving interventions in the Urmia Lake Restoration Program (ULRP), which aims to restore Urmia Lake in north-western Iran. The framework assessed the situation “ex ante” and “ex post” of the interventions under different climate change and socioeconomic scenarios.

4.2. Method

4.2.1. The water-saving intervention assessment framework

Water accounting is an approach to the presentation of information on water resources, water supply, and water use (Vardon et al., 2012). The methodology focuses on a water-balance approach where, based on conservation of mass, the sum of inflows must equal the sum of outflows plus storage (Molden and Sakthivadivel, 1999). Water accounting covers a range of methods of reporting water information (Godfrey and Chalmers, 2012). Building on the water-accounting approach, we suggest a framework that aims to provide a simple understandable overview for assessing the effectiveness of a water-saving intervention (Figure 4-1). To detect if a water-saving intervention is able reach its goal, the framework considers processes in detail. Its benefit is threefold. First, it considers future changes in water supply and demand, thus accounting for climate change and socioeconomic scenarios. Secondly, the framework differentiates between water demand and water withdrawal. This can highlight any shortage or overuse in the basin that could affect the efficacy of the water-saving intervention. Thirdly, water withdrawal, water depletion, and return flows (to surface water and groundwater) are included separately. This helps to detect the usually overlooked and undesired rebound effect. To keep it as simple as possible, the framework suggests estimating the five main components to evaluate a water-saving intervention under different socioeconomic and climate change scenarios. These components are i) *total (gross) water demand*; ii) *water supply*; iii) *water withdrawal*; iv) *water depletion;* and v) *environmental flow* in the basin.

Component 1 is *total (gross) water demand* for specific water users (agriculture, industry, and domestic) under different socioeconomic scenarios. Real demand is the key to assessing any water-saving intervention. Total water demand is equal to "net water demand divided by efficiency" and may or may not be met in a basin. If total water demand is not met in a basin, the basin faces water shortage. Historical demand can be obtained from empirical data for different sectors. Thereafter, future water demand should be calculated considering population growth and future development in the industrial and agricultural sectors. Most water-saving policies aim to control the demand in different sectors either by decreasing withdrawal (e.g., increasing efficiency) or by decreasing net demand (e.g., changing crop patterns).

Component 2 is the basin *water supply*. Total water supply includes naturalized surface flow under different climate change scenarios, extracted groundwater, and any water added to the basin water resources by being transferred from outside the basin or by desalination. The naturalized surface flow in the basin can be estimated through a simulation approach under different climate-change scenarios. The historical groundwater extraction data can be obtained from data measured on the ground. Future groundwater withdrawals can be estimated based on future water demand and the groundwater extraction regulations.

Component 3 is *water withdrawal* (also referred to as water extraction) for specific water users (agriculture, industry, and domestic) that should be estimated for different socioeconomic scenarios. Historical water withdrawal can be estimated from measured ground data. Future water withdrawal can be estimated based on the proposed interventions, if these are intended to reduce rights to withdraw water.

Component 4 is *water depletion* (also referred to as water consumption) for specific water users (agriculture, industry, and domestic). Water depletion is equal to "water withdrawal – return flow." Thus, to calculate water depletion, one needs to understand how much of the withdrawal will return to the system. A policy may reduce water withdrawal, but although that may lead to decreased return flow, it does not lead to saving the same volume of water. In a endorheic basin, change in the depletion will show the real water saved through the intervention (Seckler, 1996). Water depletion can be divided into beneficial and non-beneficial consumption. Beneficial depletion occurs when water is depleted to produce a good such as an agricultural output. Non-beneficial depletion occurs when no benefit (or a negative benefit) is derived from the depletion of water (Molden and Sakthivadivel, 1999). To prevent a decrease in return flow, a water-saving intervention should focus on reducing water depletion, either beneficial or non-beneficial.

Component 5 is *environmental flow* which is the water saved for the natural environment. It can be estimated as: "water supply – water withdrawal + surface return flow." This is compared with the intervention target and/or Environmental Flow Requirements (EFRs). The water saved for groundwater is basically return flow to groundwater which should be compared before and after the intervention to see if the intervention has had an effect on groundwater recharge or not. This is especially important in an area where the groundwater level is in a critical state.

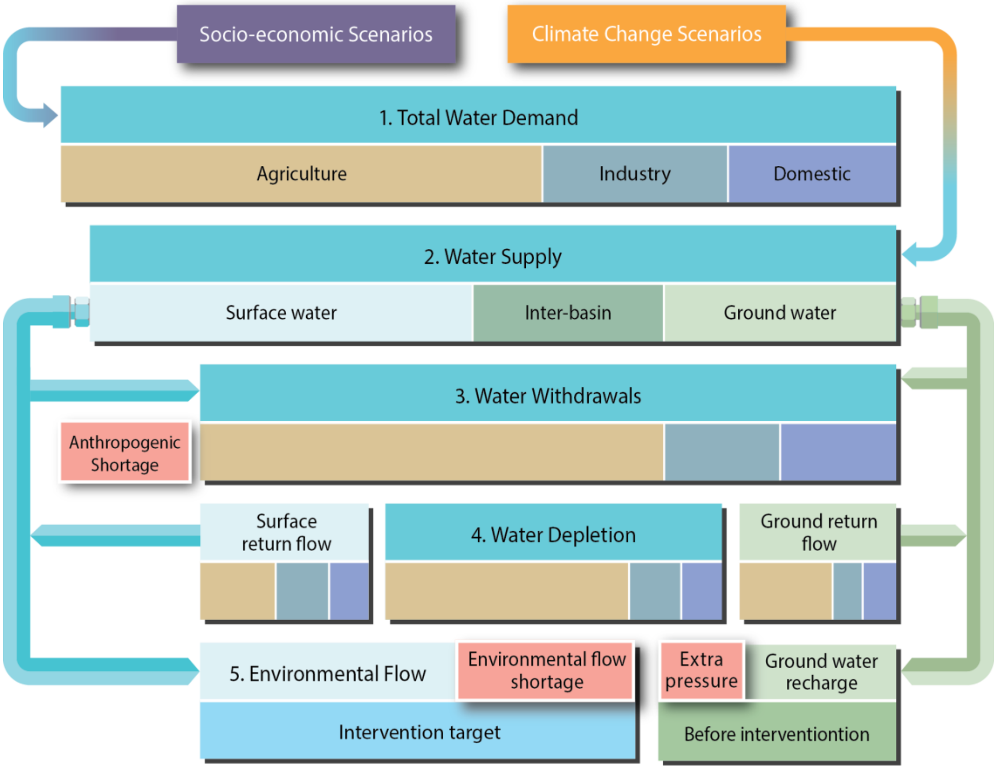


Figure 4-1 The water-saving intervention assessment framework. The framework shows how the five key components relate to the river basin water balance.

The water-saving intervention assessment framework was used to evaluate the proposed water-saving intervention as part of the Urmia Lake Restoration Program (ULRP) for the historical period, 2000–2010, and for the future time period, 2020–2030. The results were presented as the averaged value for 2005 and 2025 under two socioeconomic scenarios (usual and desirable) and two climate change scenarios (RCP2.6 and RCP8.5). Urmia Lake, located in north-western Iran (Figure 4-2), was once the largest lake in the Middle East and one of the largest permanent hypersaline lakes in the world. The lake was declared a Wetland of International Importance under the Ramsar Convention and it was designated a UNESCO Biosphere Reserve in 1976 (Eimanifar and Mohebbi, 2007). Its basin area is around 51,000 km^2, some 5,000 km^2 of which was covered by the lake (Meijer et al., 2012). The Urmia Basin has a total population of 6.5 million and is an important agricultural region (Iran Ministry of Energy, 2013a).

The average annual precipitation ranges between 200 and 300 mm, with air temperatures between 0 and -20°C in winter, and up to 40°C in summer. The Basin's climate is classified as arid to semi-arid, making agriculture there highly dependent on irrigation (Iran Ministry of Energy, 2014a). Total irrigated area in the basin is 5,119 km^2, and 89% of available water is used for irrigation (water withdrawals). The main crops are wheat, barley, alfalfa, potato, tomato, sugar beet, and apple. Current irrigation efficiency is estimated to be 42% for trees and gardens and 34% for farms (Iran Ministry of Energy, 2014i).

Over the last 20 years, the surface area of Urmia Lake has decreased considerably (Figure 4-2). As a result, the salinity of the lake has also increased sharply, disturbing ecosystems, local agriculture and livelihoods, regional health, and tourism (UNEP, 2012). To address the unsustainable situation, the government of Iran announced a national program, the "Urmia Lake Restoration Program" (ULRP), in July 2013. The government committed a budget of US$5 billion to the program (Guardian, 2015), the main goal of which is revival of the life cycle of the lake within 10 years. The plan also aims to promote the development of sustainable agriculture.

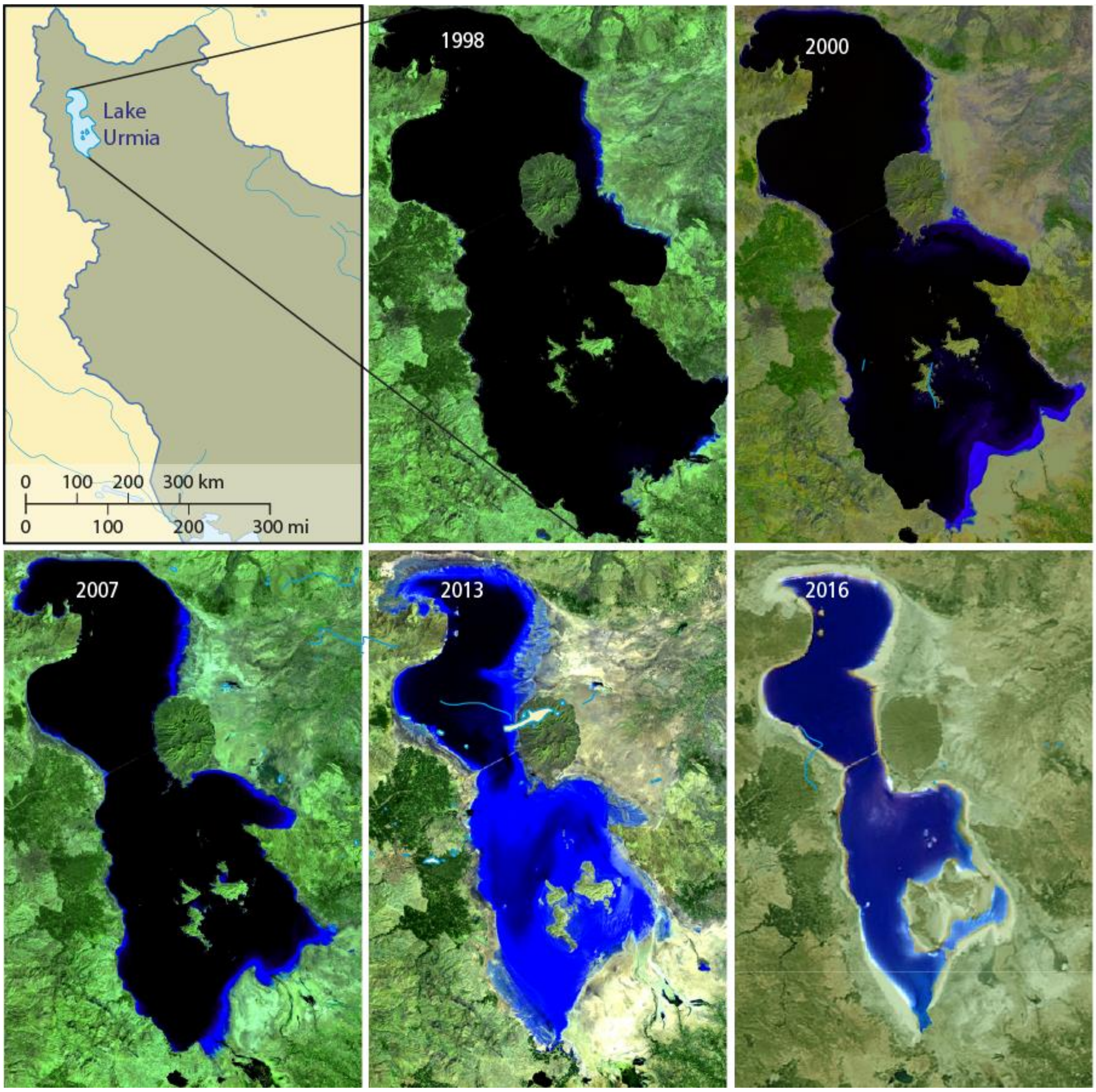


Figure 4-2 Urmia Lake location in Iran and the desiccation trend between 1998 to 2016 (USGS, 2016)

4.3. Urmia Lake Restoration Program (ULRP)

By deteriorating condition of Urmia Lake, the Iranian government's approved and established the "Urmia Lake Restoration Program." The ULRP was approved as a ten-year program (2015-2025) with three phases: i) stabilizing the current status; ii) restoration; iii) sustaining the restoration.

The ULRP uses six categories of measures:

Category 1 is *control and reduction of water depletion in the agricultural sector*. This category suggests the purchase of 40% of farmers' water rights by the government to the lake, along with increasing efficiency and productivity in the agricultural sector. The measures to be taken in this category will have a direct impact on inflow. While the URLP expected this measure to add $1430\times10^6 m^3 yr^{-1}$ to inflow, the actual quantitative impact is unclear.

Category 2 is c*ontrol and reduction of withdrawal from surface and groundwater resources in the Basin.* This means holding the water depletion at its current rate and preventing unauthorized water withdrawals by halting development projects and passing supporting legislation. While this will not directly increase inflow, it will prevent further reduction.

Category 3 is *initiatives on protection and mitigation of negative impacts*. These will focus on researching and studying health problems caused by the desiccation of the lake and also on creating alternative employment opportunities. While not directly impacting lake inflow, this will support other categories by improving people's livelihoods.

Category 4 is s*tudies and software measures*. While also not directly increasing inflow, this will increase support for other categories by promoting public awareness and capacity building, and developing a decision-support system.

Category 5 is *facilitation and increase of the water volume entering the lake through structural measures.* This category promotes the building of a network of waterways to bring available river water into the lake.

Category 6 is *water supply from additional water resources.* This category will directly increase lake inflow. It has been predicted that $690\times10^6 m^3$ will be transferred from the Zaab Basin to the Urmia Basin. In addition, the ULRP predicts that up to $300\times10^6 m^3 yr^{-1}$ of urban and industrial wastewater will be directed into Urmia Lake.

For this study, we assumed successful ULRP implementation, namely, that water withdrawals in the basin will be successfully controlled (category 2) or that structural measures will be able to direct the surface flow available in the basin to the lake (category 5) (ULRP, 2017). While the quantitative effect of measures aiming directly to increase the inflow is unclear, those having a direct impact on inflow are:

- Reduction of 40% of ground and surface water allocated to the farmers through a direct purchasing system run by the Ministry of Energy over a five-year period.
- Allocation of funds and supply of the required technologies by the government to increase the efficiency of usage of the remaining water.
- Planning by the Ministry of Jihad-e-Agriculture to enhance the productivity of 60% of the remaining water volume still used for irrigation.
- Appropriation of the required funds and accelerated transfer of water from the Zaab and Silveh rivers to Urmia Lake Basin.
- Transfer of treated wastewater from the Urmia Lake Basin into Urmia Lake.

The main objective of this study was to assess the impacts of the measures listed on the surface inflow into Urmia Lake under different climate change and socioeconomic scenarios. In what follows, we explain the methodology we used to estimate the framework components both before and after ULRP to assess if ULRP is able to reach its goal of saving $3100\times10^6 m^3 yr^{-1}$ inflow to the lake.

4.3.1. Total water demand under ULRP and different socioeconomic scenarios

Agricultural sector *total water demand* under URLP: The Iran Ministry of Energy (2014i) reported the total irrigation demand based on the cultivated area of the basin, cropping patterns, planting and harvesting dates, irrigation management and efficiency. ULRP aims to control development in the agricultural sector and reduce total water demand by purchasing 40% of the existing water rights (category 1), enhancing productivity (category 2), and increasing efficiency (category 3; ULRP, 2015).

Measures under category 1 will decrease available water by 40%. As a detailed plan of the implementation of categories 2 and 3 are not yet clear, we interpreted the main measures (ULRP, 2016b) based on available reports for the Urmia Basin. The new net water demand can be calculated based on the main measures of category 2 aiming to reduce net water demand including (ULRP, 2016b):

a) Deficit irrigation for wheat: the (SWRI) (2013) estimated that by changing the current variety to the *Pishgam* variety for the Urmia Basin, deficit irrigation of up to 10% can be conducted without a significant reduction in productivity.

b) Deficit irrigation for barley: the *Bahman* variety was applied based on the (SWRI) (2013) recommendation for the Urmia Basin.

c) Replacing barley with alfalfa: the reported net irrigation demand of alfalfa is ~2300m^3/ha lower than that of barley (*Bahman* variety). The initial investigation revealed that there is potential to replace 30% of alfalfa in the area with barley, which was applied in this study (ULRP, 2017) .

d) Using greenhouse cultivation for vegetables: the (Iran Ministry of Energy, 2014f) reported that greenhouse cultivation can decrease net irrigation demand by 25% in this area for vegetables. We considered that the ULRP will be able to transfer all vegetables to greenhouses by 2025.

In addition, the new irrigation efficiency (water depleted divided by water withdrawn) was estimated based on the proposed headlines for category 2 which aim to increase irrigation efficiency by ULRP (ULRP, 2016b):

e) Increasing irrigation efficiency by applying sprinkler and drip irrigation: the current application efficiency for farming is around 50%. We substitute sprinkler irrigation, used mainly for farming, which has an efficiency in the basin of around 75%. For gardens (fruits and nuts trees) the current reported efficiency is about 62%, which becomes 90% when replaced with drip irrigation (Iran Ministry of Energy, 2014i).

f) Increasing distribution efficiency by using pipes for water distribution in the field: The average current distribution efficiency in the basin is around 85%, which increases to 95% when pipes are used (Iran Ministry of Energy, 2014i).

g) Increasing conveyance efficiency by lining canals: the average conveyance efficiency in the basin is around 80%, which increases to 90% if this is implemented (Iran Ministry of Energy, 2014i).

Regarding the topography, soil type, and water quality, up to 70% of the irrigated land has the potential to be under pressurized irrigation. We thus assumed that 70% of irrigated land will have pressurized irrigation after the ULRP (Iran Ministry of Energy, 2014f).

Domestic and industrial sectors *total water demand* under socioeconomic scenarios: Five million people were estimated to be living in the Urmia Basin in 2005. Around 3.5 million were living in urban areas and 1.5 million in rural areas, for which the total water demand was estimated by the Ministry of Energy (Iran Ministry of Energy, 2014d). There are 7,100 firms in the basin including textile, food, metal and steel, wood, mining, and machinery manufacturing, for which the total water demand was reported by the Ministry of Energy (Iran Ministry of Energy, 2014d).

The population of the Urmia Basin is predicted to be around 6.5 million in the year 2025 (Iran Ministry of Energy, 2014g). The number of industrial companies is also predicted to increase to 16,352 sites in the basin. To project the total water demand for domestic and industrial sectors we looked at two scenarios: the “usual” (applying the current water distribution system) and the “desirable” (applying improvements in the water distribution system) (Iran Ministry of Energy, 2014h).

4.3.2. Water supply under different climate change scenarios

Water supply is estimated by simulating naturalized flow in the basin using the Variable Infiltration Capacity (VIC) hydrological model. In the present study we manually calibrated the VIC model (Shadkam et al. (2016a) in a systematic way, as described by (Xie et al., 2007b), using seven runoff-related model parameters, including the infiltration parameter, and three soil-layer thicknesses for the Urmia Basin. We forced the calibrated VIC for the Urmia Basin using bias-corrected daily climate model output, as developed within the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP: (Hempel et al., 2013, ISI-MIP, Warszawski et al., 2014). Data from five General Circulation Models (GCMs: MIROC-ESM-CHEM, IPSL-CM5A-LR, HadGEM2-ES, NorESM1-M and GFDL-ESM2M) were selected based on availability (Taylor et al., 2012). To cover the whole range of future greenhouse gas emissions we used the Representative Concentration Pathways (RCPSs) selecting the highest (8.5) and the lowest (2.6) (Van Vuuren et al., 2011). As GCM output differs significantly from observations, we used bias-corrected output of the GCMs to force the VIC hydrological model. Bias-corrections of daily temperature, precipitation, and wind speed were carried out using quantile mapping (Piani et al., 2010). To cover decadal variabilities we used a 10-year moving average for 2005 and the projected inflow for 2025. For more details, refer to (Shadkam et al., 2016b).

There are around 88,000 wells in the Urmia Lake Basin, of which an estimated 40,000 are unauthorized (Figure 4-3) (ULRP, 2016a). The water withdrawals from groundwater, including wells and *qanats*, were reported by the ULRP (ULRP, 2016a). These withdrawals represent groundwater supply for the historic period, 2000–2010. Based on the ULRP, there needs to be a 40% decrease in water withdrawals in agriculture, of which $500\times10^6 m^3 yr^{-1}$ would be reduced from groundwater abstraction (ULRP, 2016b). However, a substantial portion of industrial and domestic water demand will still be met from groundwater resources. This means that more extractions from groundwater will be expected under the two different socioeconomic scenarios.

In addition, $690\times10^6 m^3 yr^{-1}$ of inter-basin transfer water from the Zaab Basin has been added to the available water.

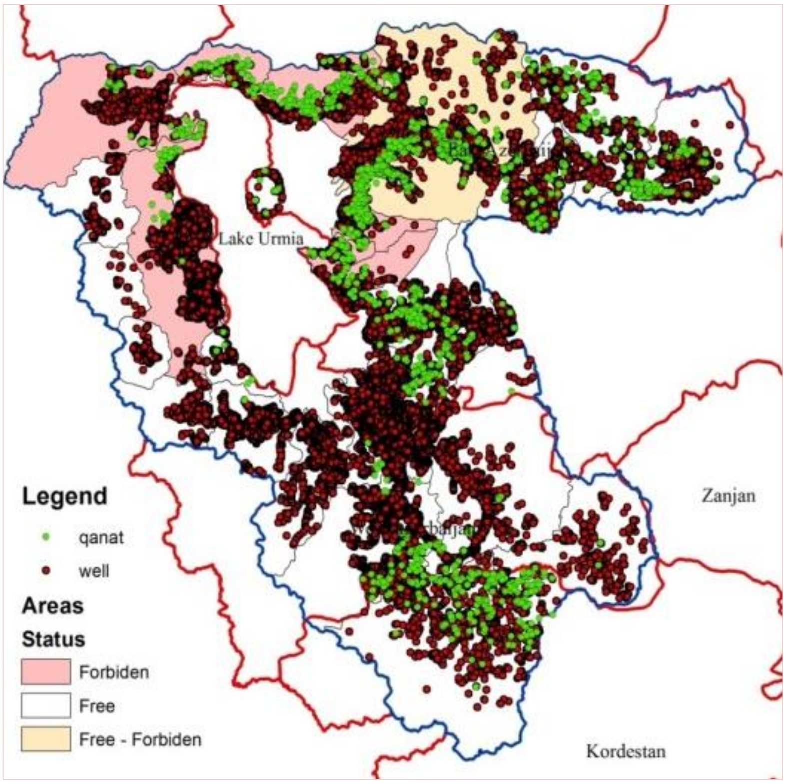


Figure 4-3 Groundwater withdrawals in Urmia basin by wells and qanats, the all wells located in forbidden area (pink) and some in yellow are illegal (ULRP, 2016a)

4.3.3. Water withdrawal and depletion under ULRP and different socioeconomic scenarios

Agricultural sector: the amount of *water withdrawal* depends on how much water is available for the agricultural sector. If the available water is less than total demand, the water withdrawals will be available for agriculture; otherwise water withdrawals are equal to total water demand.

Water depletion equals Water withdrawals minus Return flow. Therefore, we need to first estimate Return flow. Simulation studies estimated the current total return flow (to surface and ground water) in Urmia Lake basin to be between 44% to 51% of irrigation water withdrawals (Ahmadzadeh et al., 2015, Farokhnia, 2015). However, the proportion of groundwater and surface water is not determined in these studies. To estimate the proportion of surface and ground return flow we used reports by the Ministry of energy which estimated surface return flows from irrigation to be around $950\times10^6 m^3$ of $5345\times10^6 m^3$ (~18% of water withdrawal) in Urmia basin, based on field observation (Iran Ministry of Energy, 2014c). Therefore, if we consider 48% (average value of reported total return flows) of current withdrawals to return to the system, the return flow to the groundwater should be around 30% (48%-18%). Toloei et al. (2015) assessed the effect of changing from gravity irrigation to pressurized systems applying the Soil and Water Assessment Tool (SWAT) for Urmia basin. Similar to this study, they assumed transforming of gravity irrigation to drip irrigation for orchard and to sprinkler irrigation for farmland. Their results showed a decrease of 60% in groundwater return flow. They also reported an ignorable amount of surface return flow in case of pressurized irrigation. Their results were used for estimating surface and groundwater returnflow after ULRP.

Domestic and industrial sectors: as with the total water demand from the domestic and industrial sectors, the water withdrawals, return flow, and consequently water withdrawals are provided by the

Macro Planning Bureau of the Iranian Ministry of Energy for both the usual and desirable scenarios in 2005 and 2025 (Iran Ministry of Energy, 2014d, Iran Ministry of Energy, 2014e). However, the ULRP aims to treat and direct all urban (not rural) and industrial wastewater to the lake. To estimate how much domestic and industrial water will return to surface and groundwater, we applied the ULRP measure aimed at treating and directing all urban (not rural) and industrial wastewater to the lake. Therefore, after ULRP the estimated urban and industrial wastewater are added to the surface water flows.

4.3.4. Environmental inflow under different climate change and socioeconomic scenarios

The *environmental flow* equals *water supply* – *water withdrawals* + surface return flows. This was estimated for four different scenarios, combining climate scenarios and socioeconomic scenarios.

The effectiveness of each ULRP measure in terms of changing environmental flow (surface inflow) was also estimated. The effectiveness of agricultural measures in environmental flow terms can be estimated as the difference between water withdrawals for agriculture and surface return flow from agriculture before and after the ULRP. Wastewater measures will only affect surface return flow; thus the effectiveness of wastewater measures on environmental flow is shown in the urban and industrial wastewater which would be conveyed to the lake under the ULRP. The results compared with the ULRP target, namely, the environmental flow requirements (EFRs) estimated by (Abbaspour and Nazaridoust, 2007).

4.4. Results

Following, first the estimation of five framework's components presented. Since then, by comparing different components the frameworks' results for different historical period and future perspective under climate change and socioeconomic scenarios analysed.

4.4.1. Total water demand under different socioeconomic scenarios

Agricultural sector: There were 155,506 and 356,420 ha orchard and croplands in Urmia Basin, for which total irrigation net and total (gross) demand have been reported $2{,}600\times10^6 m^3 yr^{-1}$ and $6{,}669\times10^6 m^3 yr^{-1}$, respectively (Iran Ministry of Energy, 2014i). The irrigated land will remind the same after ULRP. However, ULRP aims to reduce irrigation net demand and increase in irrigation efficiency, which would reduce the total demand.

The proposed measures to reduce net irrigation demand before and after ULRP presented in the Table 4-1. The total net water demand would decrease $183\times10^6 m^3 yr^{-1}$ by applying all measures in the covered area. It means that the net agricultural water demand of the basin will decrease from 2600 to $2417\times10^6 m^3 yr^{-1}$ after ULRP (Table 4-1).

Table 4-1 Urmia Lake Restoration Program (ULRP) proposed measures and average net irrigation demands in the covered area and Urmia basin.

Proposed measure		Covered area (ha)	Net irrigation demand ($\times 10^6 m^3$)	
			Before ULRP	After ULRP
a)	**Deficit irrigation for wheat**	164,225	448	389
b)	**Deficit irrigation for barley**	35,588	72	65
c)	**Replacing alfalfa with short growing season barley**	121,382	872	760
d)	**Greenhouse cultivation for vegetables**	3,947	19	14
Total		325,143	1,410	1,228

The second group of agricultural measures focuses on increasing water use efficiency. The current and expected Conveyance efficiency (E_c), Distribution efficiency (E_d), Application efficiency (E_a) are presented in the table 4-2. As we can see in the table the total irrigation efficiency, $E_c \times E_d \times E_a$, for orchards is expected to increase by 77% and for croplands by 64%.

Table 4-2 The current reported efficiency and predicted efficiency after ULRP in Urmia basin.

Application	Before ULRP				After ULRP			
	E_c	E_d	E_a	E_{Total}	E_c	E_d	E_a	E_{Total}
Orchard	80%	85%	62%	42%	95%	90%	90%	77%
Cropland	80%	85%	50%	34%	95%	90%	75%	64%

*: (E_c): Conveyance efficiency, (E_d): Distribution efficiency, (E_a): Application efficiency, $E_{Total} = Ec \times Ed \times Ea$

To calculate total (gross) agricultural demand of the basin after and before ULRP the estimated net water demand divided by the estimated efficiencies of the cropland and orchards. The results showed that the *Total demand* for the orchard decrease from $2{,}297 \times 10^6 m^3 yr^{-1}$ to $1{,}502 \times 10^6 m^3 yr^{-1}$ and for cropland decrease from $4{,}372 \times 10^6 m^3 yr^{-1}$ to $2{,}599 \times 10^6 m^3 yr^{-1}$ and in total decrease from $6{,}669 \times 10^6 m^3 yr^{-1}$ to $4{,}101 \times 10^6 m^3 yr^{-1}$.

Domestic and Industrial sector: the total demand in the historical period (2000-2010) for domestic and industrial sectors is reported around $343 \times 10^6 m^3 yr^{-1}$. By increasing population and industry development, *the total demand* will increase to $994 \times 10^6 m^3 yr^{-1}$ and $1{,}214 \times 10^6 m^3 yr^{-1}$ for desirable and usual scenarios, respectively.

Table 4-3 Urmia basin historical and future total water demand, water withdrawals form ground and surface water, water depletion and return flows to surface and ground water for different sectors under different socioeconomic scenarios ($\times 10^6 m^3 yr^{-1}$).

Component	**Period**	**Scenario**	**Domestic**				**Industry**		**Agriculture**		**Total**
			Urban		**Rural**						
			SW	**GW**	**SW**	**GW**	**SW**	**GW**	**SW**	**GW**	
Total water demand	History (2000-2010)	Before ULRP	207		45		90		6669		7011
	Future (2020-2030)	After ULRP/desirable Sc.	560		106		329		4084		5079
		After ULRP/Usual Sc.	611		110		493				5297
Water withdrawal	History (2000-2010)	Before ULRP	89	118	7	39	0	90	3214	2142	5708
	Future (2020-2030)	After ULRP/desirable Sc.	241	319	16	90	0	329	2450	1633	5075
		After ULRP/Usual Sc.	263	348	17	93	0	493			5297
Water depletion	History (2000-2010)	Before ULRP	41		12		17		2758		2855
	Future (2020-2030)	After ULRP/desirable Sc.	100		27		59		2885		3074
		After ULRP/Usual Sc.	110		21		89				3108
Return flow	History (2000-2010)	Before ULRP	0	166	5	28	10	63	911	1660	2844
	Future (2020-2030)	After ULRP/desirable Sc.	321	137	11	66	188	81	208	987	1999
		After ULRP/Usual Sc.	351	150	14	74	283	121			2188

4.4.2. Water Supply under different climate change scenarios

The average simulated naturalized runoff (using the VIC model) for the periods 2000-2010 and 2010-2030 (under RCP 2.6 and 8.5) derived from five GCM are presented in table 4-4. Comparing the current available water, the simulation results for the period of 2020 to 2030 would reduce around 3% and 15% under RCP 2.6 and RCP8.5, respectively.

To estimate the total water supply, ground water withdrawals were added to the naturalized river flows. Total groundwater withdrawals in 2005 was $2{,}390\times 10^6 m^3 yr^{-1}$ for which $2{,}142.4\times 10^6 m^3 yr^{-1}$ is for agricultural used. Based on ULRP agricultural water withdrawals will decrease 40%, from which around $500\times 10^6 m^3 yr^{-1}$ is from groundwater. However, regarding socioeconomic development of the basin, the groundwater withdraws will increase for domestic and industry sectors, under desirable and usual socioeconomic development. This added to $690\times 10^6 m^3 yr^{-1}$ the target for water transfer from Zaab basin. In addition, the result of total water supply present in Figures 4-4-a (historical period), 4.4-b (RCP 8.5 and usual socioeconomic scenario), and 4.4-c (RCP 2.6 and desirable socioeconomic scenario), in the total water supply bar. Total available water showed in Table 4-4.

The water withdrawals from groundwater, including wells and qanats, were reported $2389\times 10^6 m^3$ for 2005 (ULRP, 2016a). This considered as available groundwater for historical period. Based on ULRP 40% of water withdrawals in agriculture has to be decreased. On the other hand, substantial portion of industry and domestic water will be provided from groundwater which will cause increase groundwater withdrawals. Therefore, as we assumed the successful implementation of ULRP, the available ground water for 2025 estimated to be around and $2371\times 10^6 m^3$ for desirable scenario and $2568\times 10^6 m^3$ for Usual scenario. In addition, Inter-basin water transfer, URLP has started to facilitate $690\times 10^6 m^3 yr^{-1}$ to Urmia basin from Zaab basin, which has been added in available water.

Table 4-4 Urmia basin water supply for historical period and future under RCP2.6 and RCP8.5 ($\times10^{6}m^{3}yr^{-1}$)

Component	Period	Scenarios	Naturalized surface	Inter-basin	Groundwater		Total	
					desirable Sc.	Usual Sc.	desirable Sc.	Usual Sc.
Water supply	History (2000-2010)	Before ULRP	4676.4	0	2389		7065	
	Future (2020-2030)	After ULRP/RCP2.6	4553.3	690	2371	2568	7524	7811
		After ULRP/RCP8.5	3940.8	690			7109	7198

4.4.3. Water withdrawal and depletion under different socioeconomic scenarios

Agricultural sector: The historical *Water withdrawals* (available water) for agricultural is around $5,356\times10^{6}m^{3}yr^{-1}$ (Iran Ministry of Energy, 2014i), which is much less than total demand ($6,669\times10^{6}m^{3}yr^{-1}$). Proportionality we estimated that only $2,088\times10^{6}m^{3}yr^{-1}$ of $2,600\times10^{6}m^{3}yr^{-1}$ net demand can be fulfilled. ULRP would reduce total demand to $4,048\times10^{6}m^{3}yr^{-1}$ which is less than the basin available water for agricultural sector ($5,356\times10^{6}m^{3}yr^{-1}$). Therefore, *water withdrawals* are equal *total water demand* after ULRP. In addition, by doing full irrigation, farmers can meet the net demand, which had been calculated $2,417\times10^{6}m^{3}yr^{-1}$ after ULRP.

The estimated return flow for historical period is $911\times10^{6}m^{3}yr^{-1}$ and $166\times10^{6}m^{3}yr^{-1}$ to surface and ground flow, respectively. *Water Depletion* is equal *water withdrawals - return flow*. Therefore, the historical water depletion is estimated to be $2758\times10^{6}m^{3}yr^{-1}$. For which, $2088\times10^{6}m^{3}yr^{-1}$ is beneficial water demand (net demand) and $670\times10^{6}m^{3}yr^{-1}$ is none beneficial. After ULRP, the return flow will decrease to $208\times10^{6}m^{3}yr^{-1}$ and $987\times10^{6}m^{3}yr^{-1}$ for surface and groundwater, respectively. Therefore water depletion is estimated to be around $2885\times10^{6}m^{3}yr^{-1}$ after ULRP, for which $2417\times10^{6}m^{3}yr^{1}\times10^{6}m^{3}yr^{-1}$ is beneficial and $468\times10^{6}m^{3}yr^{-1}$ is none beneficial depletion.

Domestic and industrial sectors: As the domestic and industrial demands were always fulfilled in the basin, the historical *water withdrawals* were equal to the *total water demand*. Based on the reported domestic and industrial return flow, the *water depletion* is estimated around $70\times10^{6}m^{3}yr^{-1}$ (Iran Ministry of Energy, 2014d).

After ULRP, the domestic and industrial water demand will be fully fulfilled in Urmia basin, therefore *water withdrawals* will be same as water demand in these two sectors as well. The predicted return flows for these two sectors would be $553\times10^{6}m^{3}yr^{-1}$ and $590\times10^{6}m^{3}yr^{-1}$ for desirable and usual scenarios, respectively (Iran Ministry of Energy, 2014g). Therefore, water depletion is around $127\times10^{6}m^{3}yr^{-1}$ and $131\times10^{6}m^{3}yr^{-1}$ for desirable and usual scenarios, respectively. The summary of the results presented in Table 4-3.

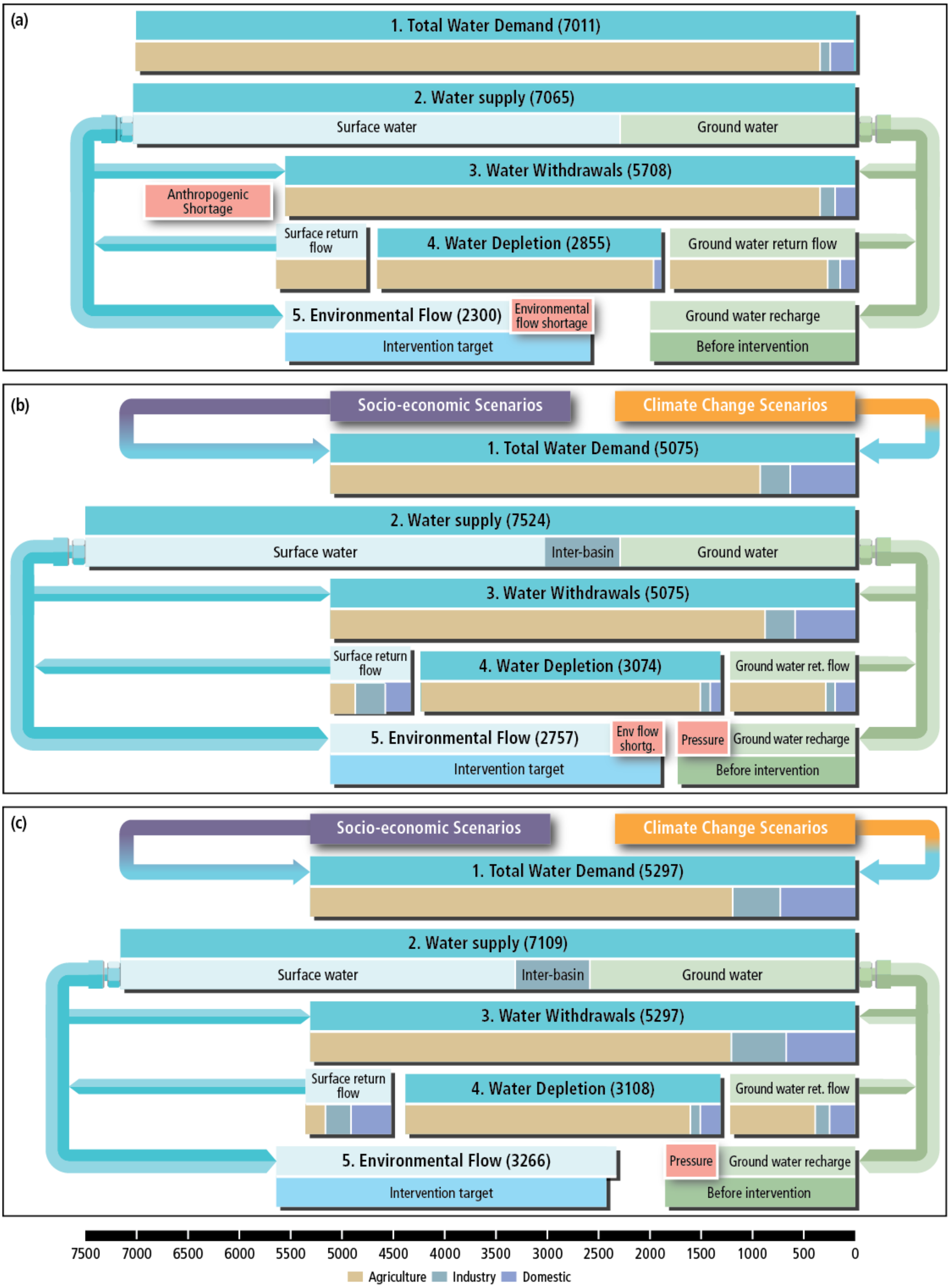


Figure 4-4 Water-saving intervention assessment framework for a) historical period (2000-2010) and future perspective (2020-2030); b) under RCP8.5 and usual socioeconomic scenarios and c) under RCP2.6 and desirable socioeconomic scenarios ($\times 10^6 m^3 yr^{-1}$).

4.4.4. Environmental flow under different climate change and socioeconomic scenarios

Environmental flow is equal *water supply – water withdrawals + surface return flows* which was equal 2300×10^{6}m^{3}yr^{-1} for historical period. This is in the range of reported historical inflow to the lake (ULRP, 2016b). Figure 4-5 showed the inflow to the lake under different climate change and socioeconomic scenarios also effectiveness of each measure on the flow. The results showed that if ULRP succeed to perform all measures, it can increase inflow by 49%, 51%, 53% and 58%, under RCP2.6 and desirable socioeconomic , RCP2.6 and usual socioeconomic , RCP8.5 and desirable socioeconomic , and RCP8.5 and usual socioeconomic , respectively. However, only under RCP2.6 and under both socioeconomic scenarios, the inflow can just reach ULRP target which is 3100×10^{6}m^{3}yr^1. This is not the case for RCP8.5 scenario in none of socioeconomic scenarios. The most effective measure is inter-basin transfer and after that wastewater measure. The agricultural measure impact is not considerable.

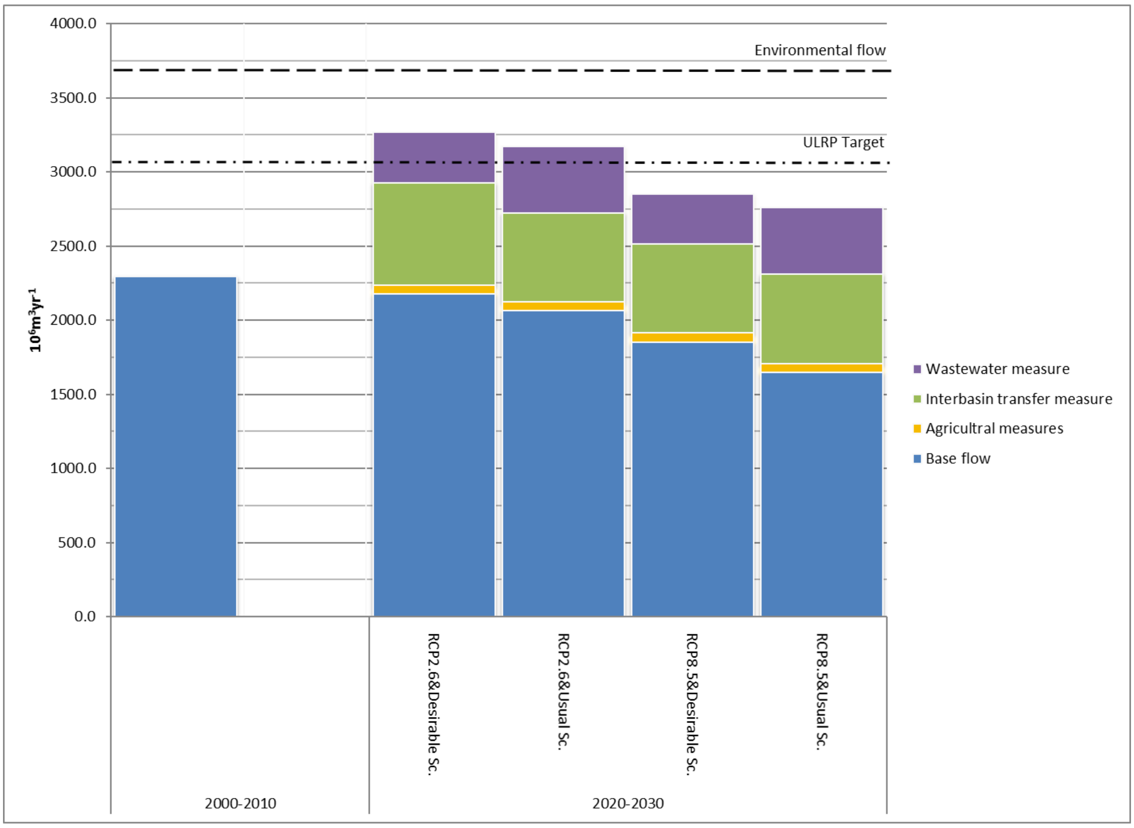


Figure 4-5 Historical inflow to Urmia Lake (2000-2010) and under different two climate change scenarios (RCP2.6 and RCP8.5) and two different social-economic scenarios (desirable and usual) effectiveness of each measure

4.4.5. Water-saving intervention assessment framework for ULRP

Figure 4-4 illustrates the water-saving intervention assessment framework for ULRP for historical period (a), future most optimistic climate change (RCP2.6) and socioeconomic (desirable) scenarios (b) and future most pessimistic climate change (RCP8.5) and socioeconomic (usual) scenarios (c).

As can be seen in Figure 4-4-a *Total water demand* for historical period was estimated to be around 7,011×10^{6}m^{3}yr^{-1}, which is almost equal *Water supply*, 7,065×10^{6}m^{3}yr^{-1}. This shows that for this period environmental flow requirements are not met, thus the basin experiences water scarcity. Therefore, it is not surprising that *Water withdrawals*, 5,700×10^{6}m^{3}yr^{-1}, was lower than total water demand. The difference between the two has been indicated to represent the basin anthropogenic water shortage

(Figure 4-4-a). As domestic and industrial water demand are fully met, this shortage is fully attributed to for agricultural sector. It means that there have already been a (gross) shortage of 1,313×10^6m^{3}yr^{-1} (~20% of Total water demand) for the agricultural sector in the basin. This is confirmed by the Ministry of Energy (Iran Ministry of Energy, 2014i), particularly for the downstream part of the basin (near Urmia Lake).

As can be seen in Figures 4-4-b and 4-4-c, representing estimates for the period 2020-2030, the total demand will decrease by 5,000×10^6m^{3}yr^{-1} and 5,300×10^6m^{3}yr^{-1} for desirable and usual scenarios, respectively. On the other hand, the *Water supply* would be 7,614×10^6m^{3}yr^{-1} and 7,199×10^6m^{3}yr^{-1} under RCP2.6 and RCP8.5, respectively, more than Total water demand. This shows that there would be no agricultural water shortage in the basin anymore. In the other words, ULRP would provide the full irrigation possibility for the farmers and cover the shortage.

Water depletion for all sectors is estimated at 2,855×10^6m^{3}yr^{-1} for historical period. Due to agricultural shortage in the basin only 2,088×10^6m^{3}yr^{-1} of 2,600×10^6m^{3}yr^{-1} of the net water demand was fulfilled. After ULRP, the water depletion is estimated to increase to 3074×10^6m^{3}yr^{-1} and 3108×10^6m^{3}yr^{-1} for desirable and usual scenarios, respectively. This is because of two reasons. First, reason is increase in water depletion due to growing population and industrial development. The second reason, as explained above, is that ULRP would provide enough water, due to increasing irrigation efficiency, to fully meet irrigation water demand and to prevent agricultural water shortage in the basin. This means that the entire agricultural net demand (2,417×10^6m^{3}yr^{-1}) would be fulfilled in effect of ULRP. Therefore, although ULRP would decrease total water demand (from 6,669×10^6m^{3}yr^{-1} to 4,101×10^6m^{3}yr^{-1}) and total water withdrawals (from 5,356×10^6m^{3}yr^{-1} to 4,101×10^6m^{3}yr^{-1}) but will increase water depletion (from 2,088×10^6m^{3}yr^{-1} to 2,417×10^6m^{3}yr^{-1}). It implies that the interventions in agriculture, as proposed in the ULRP will not lead to real water saving in the basin. On the contrary, the proposed interventions would lead to an increased amount of water used for agriculture.

Environmental flow is estimated for four different scenarios, and the results show that ULRP is likely to reach its goal only under limited climate change. In addition, by decreasing water withdrawals from 5,356×10^6m^{3}yr^{-1} to 4,101×10^6m^{3}yr^{-1}, the surface water withdrawals would decrease from 3,214×10^6m^{3}yr^{-1} to 2,450×10^6m^{3}yr^{-1} (763×10^6m^{3}yr^{-1} reduction) as 60% of total withdrawal by the agricultural sector is from surface water). However, the surface return flows would decrease sharply from 910×10^6m^{3}yr^{-1} to 208×10^6m^{3}yr^{-1} (702×10^6m^{3}yr^{-1} reduction) by increasing the application of pressurized irrigation systems. This means that ULRP may decrease return flows by 702×10^6m^{3}yr^{-1}. Thus, in practise ULRP agricultural measures would only help to save water 62×10^6m^{3}yr^{-1}. This is far below the expected amount. However, based on the proposed policy will lead to an increase urban and industrial return flow from (treated waste water) that is conveyed to the Lake. This will add around 500×10^6m^{3}yr^{-1} to surface return flows. Before implementing the ULRP the return flow went back to the groundwater. So the proposed change will cause a considerable reduction in return flow to groundwater. Furthermore, the groundwater return flows from the agricultural sector would decrease from 1,660×10^6m^{3}yr^{-1} to 997×10^6m^{3}yr^{-1} after ULRP.

4.5. Discussion

To achieve a sustainable water balance for all water users in a basin it is necessary to identify, quantify, and report water-related information in a structured way. To achieve this, several national and international organizations have introduced different water-accounting frameworks. Some examples of water accounting systems are the System of Environmental–Economic Accounting for Water (SEEAW) (UN, 2003), Water Footprint Accounting (Hoekstra et al., 2009) and Water

Accounting plus (WA+) (Karimi et al., 2013a). However, as none of the frameworks was specifically designed to assess a water-saving intervention, their results are not suited to adequately inform policy makers on the efficacy of water-saving interventions. The water-saving assessment framework introduced in this study assists in generating a simple and informative overview that can be used to evaluate proposed interventions. Firstly, it takes into account uncertainties in water supply and water demand by including climate change and socioeconomic scenarios. Secondly, the role of the rebound effect can be analysed systematically by explicitly distinguishing between water withdrawal and water depletion. Thirdly, it discloses any possible shortage or over-exploitation in the basin by an explicit recognition of total water demand and water withdrawals. The framework promotes an improved understanding of the current state of basin water resources, future uncertainties and barriers and opportunities for real water saving in a water-stressed basin. The framework also can be used to evaluate the impact of water-saving policies on groundwater resources.

The application of the framework to the Urmia Lake Basin revealed that under a limited socioeconomic and climate change scenario (RCP 2.6), the policy could reach the water-saving target. This, however, assumes that the ULRP is fully implemented, which is actually unlikely. It is thus possible that the ULRP will not achieve its stated goal, despite the huge investment and the social and economic impacts of the proposed interventions. The framework made clear a few reasons for the poor performance. The first is the rebound effect. However much ULRP decreases gross surface withdrawals, it will cause almost the same reduction in surface return flow. This means that although average irrigation efficiency would improve from 38% to 84%, the ULRP’s agricultural measures would not lead to the expected change in inflow. This can be explained by the concept of effective irrigation rather than classical irrigation efficiency. The ULRP aims to increase classical efficiency, which is water depletion divided by water withdrawals, whereas effective efficiency is crop-effective use of applied irrigation water (water depletion) divided by the effective inflow less the effective outflow (water withdrawals – return flows) (Seckler, 1996). The effective irrigation efficiency for the Urmia Lake basin is thus around 75% in the current situation. This relatively high effective efficiency for the basin shows that there is not that much room to improve the efficiency. These results are consistent with Alizadeh and Keshavarz (2005) who assessed the status of irrigation efficiency in Iran. They indicated that due to high effective efficiency in Iran, there is not much real water saving to be had through irrigation efficiency improvement. Having said that, in this study it was assumed that the authorities are able to control water extraction and land expansion, which is highly unlikely. Berbel et al. (2015) did a comprehensive literature review about linking water savings with water diversion and water depletion, including both theoretical models and empirical evidence. They concluded that if land expansion and water rights are not strictly controlled in a water-saving intervention, increasing rather than decreasing water depletion is to be expected. The results of this study also support the study by Ahmadzadeh et al. (2015). Their simulation results showed that pressurized irrigation can reduce water uptake about $165\times10^{6}m^{3}yr^{-1}$ compared to current surface irrigation in the Zarrineh Rud Basin, which is the main sub-basin in the Urmia Basin. They also indicated that pressurized irrigation reduces the return flow by about the same amount, which results in no significant change in total inflow to Urmia Lake. Moreover, the pressurized system mainly changes the monthly pattern of streamflow. It causes increased streamflow in the May-June period and decreased streamflow in the August-November period; however, the annual average water inflow to the lake remains almost the same. Farokhnia (2015) simulated a transformation from furrow irrigation to drip irrigation (for orchards) and sprinkler irrigation (for farmland) for the Urmia basin, applying the SWAT model. Their results showed that improving irrigation efficiency in the Urmia basin would decrease water withdrawals by 45%. However, real water saving would only be around 13% if the farmers keep deficit irrigation, and otherwise only 5%.

The second reason for the possible poor performance of the proposed interventions overlooks the fact that the basin has already faced around $1{,}314\times10^6 m^3 yr^{-1}$ water shortage in the agricultural sector. Therefore, the net demand will not be fully met in the reference period 2000-2010, which means that farmers are already experiencing water shortage. Unwillingness to perform deficit irrigation and low productivity have been reported in many parts of the basin, in particular in the downstream parts around the Lake (Iran Ministry of Energy, 2014i). By increasing irrigation efficiency, the total water demand will be less than available water, implying that the farmers can withdraw the amount they need and meet the full irrigation demand. Therefore, the water depletion increase will be ~17%. In the other words, implementing the proposed interventions (ULRP) will compensate for the anthropogenic shortage which the basin population has already faced, rather than save water for the environment. This effect can be referred to as the *shortage effect*. Although this effect can play a serious role in interventions aiming to save water for the environment, to the best of our knowledge this has not been remarked upon in the previous literature.

The third reason for the possible poor performance of the proposed interventions is ignoring the impact of future changes. The naturalized surface water of the basin will decrease from around 3 to 15% under RCP2.6 and RCP8.5, respectively. This has not been considered in the policy. Ignoring the impact of climate change is a very critical issue, with most of the scenarios predicting water supply decline in the semi-arid areas (IPCC, 2014b). Another relevant change is the possible increase in water demand due to socioeconomic development. However, as the ULRP aims to convey the treated wastewater to the lake, socioeconomic development can also increase the amount of wastewater, which will eventually add to lake inflow. However, this is not a sustainable solution because it decreases groundwater recharge and thus will increase pressure on groundwater resources, which are already heavily used.

The results of this study show that the performance of the proposed interventions is more sensitive to changes in climate compared to socioeconomic changes. This is for two reasons. First, over 90% of the water is depleted by the agriculture sector, so that changes in population size and industrial developments have a relatively low impact on water demand compared to the agriculture sector. Second, based on the ULRP the domestic and industrial wastewater will be treated and added to the lake inflow. Therefore, by increasing domestic and industrial water withdrawal, this return flow will also increase.

The framework showed that the most secure way to increase real water saving is by reducing water depletion. This is a clear indicator of water saving. The framework highlighted that agricultural depletion amounts to 97% and 91% of total water depletion, before and after the ULRP, respectively. It is thus recommended to reduce both beneficial and non-beneficial water depletion to save water in the Urmia Basin. Although agricultural measures may not reduce beneficial depletion as planned (because of the *rebound* and *shortage* effects), they would decrease non-beneficial depletion by 30%. Another measure to reduce non-beneficial withdrawals can be through decreasing soil evaporation in agricultural areas, particularly in irrigated land. Karimi et al. (2013b) showed that application of mulching in the Indus Basin can considerably decrease soil evaporation losses.

The reliability of assessments conducted using the proposed framework depends on the quality of data used. Any type of data could be used, including ground data, results from model simulations, estimations derived from remotely-sensed data, or even some best-guess estimations. An advantage of using the framework is giving a clear picture of possible impacts of a water saving intervention on basin water resources and to prevent overlooking of critical issues. Therefore, it is recommended that even in case of limited data, the framework be applied to assess a proposed water saving intervention before implementing it. Using the framework to compare alternative interventions can highlight potential pitfalls and may be used to facilitate the debate among stakeholders. In this study, we used model simulation results for water supply. The rest of the data including water demand and water withdrawals derived from ground measured data. All data were provided by the Iranian government. The validity of the data was confirmed by Urmia Lake Restoration Committee. However, all data have some level of uncertainty and error, in particular those parameters that are difficult to be verified such as return flow. Therefore, the numbers used for the purpose of demonstrating the framework in this study should be revised when more accurate data become available.

In this study, we aimed to assess the intervention target which is providing minimum $3.1\times10^6 m^3 yr^{-1}$ annual inflow for the lake and we did not assess the seasonal variations. Therefore, the results of this study don’t present dry and wet seasons distinctions. However, the framework can be used in for sub-annual periods in case of data availability. In addition, the $3.1\times10^6 m^3 yr^{-1}$ which is defined as the intervention target, is less than the proposed Urmia lake environmental flow by other studies. Shadkam et. al, (2016b) suggested $3.7\times10^6 m^3 yr^{-1}$ is needed to restore the lake. Therefore, even by providing $3.1\times10^6 m^3 yr^{-1}$ the lake might not be restored. Depending on the scope of analysis also other geographic levels of analysis can be selected. Thus, the framework could also be used at different spatial and temporal scales. By doing so, it could also be explored how policies perform at the subbasin scale of during particular time periods (e.g. during dry periods or years).

Using the framework assessments are made to explore the effect of interventions. These assessments are based on quantifiable parameters in the water domain only; while, some interventions may have other effects. For example, the inter-basin transfer is ranked as the most effective measure for increasing inflow but it may negatively affect social or ecological indicators in another basin. For such cases, an additional assessment would be required. Further, this study does not include surface-ground water interactions susceptible to changes in the water balance. Moreover for this simple demonstration case changes in agricultural demand due to climate change were ignored, among many other factors.

The simple demonstration of the framework for the Urmia Lake case made clear that the rebound effect and the actual water shortage already present may lead poor performance of intervention plans. However, as the framework was applied at the basin level, it is not clear where these effects should be controlled. For example, across the basin, potential evaporation varies strongly. This is likely to be reflected in other parameters such as irrigation efficiency, water depletion or return flow. Therefore, it is recommended to apply the framework for spatial resolutions (e.g subbasin) that suits the specific context of an intervention plan.

4.6. Conclusion

The water-saving assessment framework introduced in this study gives a simple and informative overview to policy makers to evaluate proposed interventions by estimating real water savings using a step-wise approach comprising five components: 1) Total water demand, 2) Water supply, 3) Water withdrawals, 4) Water depletion and 5) Environmental flow. The framework raises awareness on the part of policy makers of common mistakes in water-saving policies by including climate change and socioeconomic scenarios and recognition of total water demand and water withdrawals, as well as water withdrawals and water depletion. The framework is thus useful as a communication tool to increase awareness about the difference between pressure reduction (water withdrawal reduction) and impact reduction (water depletion reduction), and uncertainties in supply and demand. In addition, the framework introduces another undesired impact of water-saving policies, referred to as the shortage effect in this study. This is when a basin has already faced water shortage and water-saving policies already compensate for that shortage instead of saving water for the environment. The water-saving assessment framework also can highlight and prioritize the opportunities, which can prompt real water saving in a basin.

The application of the framework for the Urmia Lake Basin revealed that although the Urmia Lake Restoration Program helps to increase inflow to the lake, it is unlikely to meet its target. By generating a clear overview of the situation of water demand and withdrawals in the basin, the framework showed that agricultural measures would probably not have a noticeable impact on lake inflow. This is because increased irrigation efficiency would also lead to decreased return flows, and the preserved supply would merely compensate for the present water shortage experienced by the agricultural sector in the basin. Therefore, it is not recommended to increase inflow irrigation efficiency improvement in this basin if that would also serve to increase lake inflow. The results showed that additional sources of water, namely, inter-basin transfer and treated wastewater, are the most effective measures for increasing inflow. However, these interventions are also accompanied by side-effects, associated with environmentally unsustainable outcomes. Therefore, this study suggests putting more focus on decreasing water depletion, particularly in the agricultural sector, rather than focusing on decreasing water withdrawals.

CHAPTER 5:

Qualitative assessment of the Urmia Lake Restoration Program (ULRP)

Abstract

Urmia Lake, in north-western Iran, has largely dried up over the last two decades resulting in socio-environmental consequences that are similar to those of the Aral Sea disaster. In 2013, the government of Iran announced a ten-year program, the "Urmia Lake Restoration Program" (ULRP), to rescue the lake. While a quantitative assessment of the plan presented in previous chapters, has shown that that ULRP could reach its target only under a limited climate change scenario, there are additional barriers and challenges that may cause the failure of the plan or its implementation costs to become excessive. The study uses two types of qualitative data to explore these aspects: first, the findings from 40 experts who were asked to score the ULRP measures proposed to restore the lake; and second, analyses and discussions based on the in-situ observation of some of the ULRP implementation practices and modalities. The results indicate a number of challenges for the ULRP, including i) the need for proper enforcement of existing water use and development regulations; and ii) the revision of ULRP agricultural measures to control agricultural water demand (such as through crop pattern changes and targeted irrigation-efficiency improvements). The large scale infrastructure interventions, such as inter-basin water transfer, received the lowest rankings based on the experts' opinion. However, there were considerable disagreements about different measures among experts. In general, (water) demand-side measures such as crop pattern changes and irrigation efficiency improvements were more supported, as opposed to supply-side measures.

CHAPTER 5:

Qualitative assessment of the Urmia Lake Restoration Program (ULRP)

5.1. Introduction

Urmia Lake, situated in north-western Iran (Figure 5-1-a), is an important and internationally recognized natural area designated as both a RAMSAR site and a UNESCO Biosphere Reserve (Eimanifar and Mohebbi, 2007). The hypersaline lake is home to many species of reptiles, amphibians, birds, and mammals, along with a unique brine shrimp species (Asem et al., 2012). Urmia Basin supports a variety of agricultural production activities, including winter crops such as wheat and barley, summer crops such as sugar beet, perennials such as orchards and alfalfa, and livestock production (Hesami and Amini, 2016); the basin supports the livelihoods of approximately 6.4 million people (UNEP 2012). The Urmia Lake basin is located in geo-politically sensitive region, bordering Iraq and Turkey, and is characterized by a linguistically and culturally diverse population with two ethnic groups predominating, the Azeri Turks and the Kurds (Henareh et al., 2014).

The surface area of Urmia Lake has declined dramatically by 80% over the past 20 years (AghaKouchak et al., 2015). As a result, the lake’s salinity has increased sharply, which causes significant harm to its ecosystems, agriculture and livelihoods, public health, and tourism. Several studies have already warned that the future of Urmia Lake may unfold similarly to that of the Aral Sea. The latter has dried up over several decades, producing windblown salt storms and severely affecting the surrounding population (Torabian, 2015). The population density around Urmia Lake, however, is much higher than around the Aral Sea, resulting in higher risk (UNEP, 2012). Local reports have already indicated that thousands of people who were formerly living in the lake’s vicinity have abandoned the area either temporarily or permanently (RadioFarda, 2014). It is believed that people living within a radius of 500 km around the lake—estimated to be approximately 76 million people, including those living in Iraq, Turkey, Syria, Azerbaijan, and Armenia—are at risk of health and environmental consequences (Torabian, 2015); Urmia Lake’s deteriorating conditions could thus exacerbate economic, political, and ethnic tensions in this already volatile region (Henareh et al., 2014).

Hassanzadeh et al. (2012) demonstrated that decrease in surface inflow has been the main reason for lake shrinkage. A number of recent studies have also discussed reasons for the shrinkage of Urmia Lake and the possible environmental consequences (Delju et al., 2013, Farokhnia and Morid, 2014, Hassanzadeh et al., 2012, Jahanbakhsh-Asl S, 2003, Katiraei PS, 2006, Rezaei Banafsheh M, 2010).

These have all agreed that a combination of climate change and water resource development has caused the observed decline. The results of the second chapter of this theses show that while water-resource development had a substantial effect on inflow reduction, climate change and climate variability have been among the key contributors, causing about three-fifths of inflow reduction. Chapter 3 of this theses assesses the impact of the lowest and highest climate change scenarios, attributed to so-called Representative Concentration Pathways (RCPs) which represent radiative forcing of 2.6 and 8.5 W/m^2 respectively (Moss et al., 2010) on the inflow to Lake Urmia in the next century. These results show that the effects of climate change are likely to continue under both the lowest and highest RCP scenarios, making the detected trend likely to be part of a long-term change in the climate in this area.

To address this critical situation, the government of Iran announced a national program named “Urmia Lake Restoration Program” (ULRP) in July 2013. The government later approved the budget of US$5 billion for implementation of this program (Guardian, 2015), and the executive order was released on 24 June 2014. The program’s vision is to revive the life cycle of Urmia Lake and promote integrated water resource management and sustainable agricultural development in the basin. The ULRP includes three main phases over a ten-year period. The first phase (2014–2016) serves as a stabilization phase that aims to maintain the Urmia Lake water level and implement projects to decrease possible negative effects on it. The purpose of the second phase (2017–2022) is to implement measures to guarantee sufficient water supply to the lake ($3100\times10^6 m^3 yr^{-1}$) in order to gradually increase its level. The third phase (2023) is the final restoration phase which is expected to achieve the sustainability of restoration actions and ensure stabilization of the lake’s final restoration.

The Chapter 4 of this thesis introduces a quantitative framework to assess the impact of proposed ULRP measures on lake inflow under different climate change and socioeconomic scenarios. The results suggest that the ULRP may achieve its target (i.e., to increase inflow by $3100\times10^6 m^3 yr^{-1}$) under the limited climate change scenario only (RCP 2.6). Under the rapid climate change scenario (RCP 8.5), the existing ULRP policy is likely to fall short of its inflow target. The quantitative assessment also identified the most effective of all the measures evaluated as being the transfer of water from the Zaab basin to Urmia Lake, followed by the transfer of urban and industrial wastewater to the lake. Agricultural measures, such as those promoting increased irrigation efficiency, were found to have limited impact.

The study presented in Chapter 4, however, did not assess the effects of not directly quantifiable measures proposed by the ULRP such as “capacity development programs” or “controlling illegal water withdrawals.” At the same time, proposed measures such as inter-basin water transfer which ranked highest in terms of technical potential could have serious environmental and/or socioeconomic consequences that may make them difficult to implement in practice. Further, the study also assumed that the ULRP measures will be implemented as planned, which may be unlikely due to social and cultural implementation barriers. The quantitative assessment only therefore could not shed light on these aspects. Therefore, following the quantitative assessment presented in Chapter 4, the study presented here applies a simplified qualitative approach to assess the proposed ULRP measures in terms of potential challenges and barriers to their implementation.

Although quantitative approaches are essential in any policy assessment, they only account for what can be measured, thus providing only a partial insight into the problems; this insight, in turn, is shaped by uncertainties, assumptions, and ignorance (Van Der Sluijs et al., 2005). Policy decisions must often be made before conclusive scientific evidence becomes available, and potential errors or hidden barriers may cause policy implementation failure or also excessive implementation costs (Van Der

Sluijs et al., 2005). This implies the need for an additional assessment, such as one based on perspectives or mental models. Such a study can usefully supplement a conventional, quantitative technical assessment (Kim et al., 2013). Indeed, an assessment can be greatly facilitated and improved by combining qualitative (soft) and quantitative (hard) approaches (Pahl-Wostl, 2007). The inputs for qualitative analysis generally result from expert knowledge elicitations, experts judgments, qualitative fieldwork experience, interviews, observations, and documents (Patton, 2005). The experts are qualified individuals in any field of study, whose opinions may be used to clarify definitions, identify challenges, or make a value judgment regarding issues in that field (Creswell, 2013). The expert opinions are reported in a structured and sometimes quantitative form. The results can further be discussed using observers' impressions (Seyama and Nagayama, 2007).

This chapter applies a qualitative approach to assessing ULRP to give an initial picture of challenges and barriers associated with implementing and operationalization of ULRP measures. To do so, the opinions of 40 experts, who all have experience with the Urmia Lake situation through their related work and expertise, about the measures proposed to restore the lake have been solicited and collected. This was followed by three field visits by the author in 2016 to the Urmia Basin to collect local insights into the implementation of the ULRP measures. Insights based on experts' opinions solicitation, field observations, interviews, and related literature were then analyzed and synthetized, making use of synergies and complementarities across obtained data sets and supporting information.

5.2. Urmia Lake Restoration Program

By deteriorating condition of Urmia Lake, Iranian government approved and established the "Urmia Lake Restoration Program." The ULRP was approved as a ten-year program and uses six categories of measures.

The first category can be characterized as "control and reduction of water depletion in the agricultural sector." This category suggests the acquisition by the government of 40% of farmers' water rights to the lake, in combination with increasing efficiency and productivity in the agricultural sectors. The URLP expected this measure to add $1430\times10^6 m^3 yr^{-1}$ to lake inflow; however, the quantitative assessment showed that the effect might be less than $100\times10^6 m^3 yr^{-1}$ (Chapter 4).

The second category includes measures as to "control and reduction of withdrawal from surface and groundwater resources in the basin," which mainly aims to prevent unauthorized water withdrawals by restricting the number of projects under construction and by promoting and reinforcing supporting legislation.

The third category includes "initiatives on protection and mitigation of negative impacts." This category focuses more on research and study of the sources of health problems due to the Lake Desiccation, as well as creating alternative employment opportunities. Although this category of measures will not have a direct impact on lake inflow, it will support other categories by promoting sustainability of people's livelihoods.

The fourth category can be broadly characterized as "studies and software measures." The focus is on increasing public awareness and promoting capacity building, as well as developing a decision-support system. This category will play a role in the success of the other measures.

The fifth category aims to "facilitate and increase the water volume entering into the Lake through structural measures." This category aims to increase the amount of water in the rivers reaching the lake by opening and dredging the path of waterways.

The sixth category is “water supply from additional water resources.” This category will have a direct impact on increasing lake inflow. It has been planned that $690\times10^6 m^3$ will be transferred from Zaab basin to Urmia basin (ULRP, 2016b). In addition, treated urban and industrial wastewater will be transferred to the Urmia Lake, which ULRP estimates will add as much as $300\times10^6 m^3 yr^{-1}$ to the lake’s inflow. As estimated in Chapter 4, this wastewater may add as much as $450\times10^6 m^3 yr^{-1}$ to the lake’s inflow depending on alternative socioeconomic development scenarios.

The six categories of Urmia Lake Restoration Program include 27 measures:

I. Control and reduction of water depletion in the agricultural sector

1. Reduction of 40% allocated ground and surface water to the farmers through direct purchasing system by Ministry of Energy in a five-year period.
2. Planning for enhancing the productivity of 60% with left amount water used in the agriculture sector by Ministry of Jihad-e-Agriculture.
3. Allocating funds and supplying required technologies by the government to increase the efficiency of remained water usage.

II. Control and reduction withdrawal of surface and groundwater resources in Urmia Lake Basin

4. Prevention of increasing water depletion and new projects development, especially in the agricultural sector (no new water allocations).
5. Prevention of unauthorized surface water withdrawal.
6. No new dam construction projects (except Cheraghveis and Shahid Madani dams), no new irrigation and water supply network in ULB and storage of water in Madani Dam’s reservoir exclusively for the purpose of releasing it to Urmia Lake.
7. Improvement the current conditions of wells in ULB throughout installation of smart water volume counter to record and monitor withdrawal amount (in order to increase the river flow recharge to the lake).
8. Perform the necessary coordination with the judiciary in order to facilitate and accelerate the implementation of the law for illegal wells, particularly wells affecting surface water condition.

III. Initiatives on Protection and mitigation of negative impacts

9. Identification of dust source and stabilizing them.
10. Study and implementation of ecological protection program in Urmia National Park following environmental concerns.
11. Identifying effective factors on feeding major rivers leading to the lake through watershed management in order to increase recharge rate from rivers to the lake.
12. Establishment of Urmia Lake Research Center by Department of Environment.
13. Finding out the vulnerability of health, hygienic, social and environmental problems caused by Urmia Lake dry up, preparation and implementation of prevention programs reducing and preventing the likelihood risk effects.
14. Preparation of productive programs increasing alternative employment and livelihood by relevant organization.
15. Identification of halophyte species adopting well with ULB circumstances and preparation of program in order to planting selected species in the salt marshes area around the Urmia Lake.

IV. Studies and software measures

16. Development and implementation of comprehensive training program, capacity building, awareness, and getting public and local community participation in order to illustrating the consequences of current critical situation and the necessity of reviving Urmia Lake.
17. Conducting cadastral survey for ULB Lands.
18. Design and implementation of a comprehensive decision support system in ULB.
19. Study and evaluation of Shahid Kalantary causeway effects on Urmia Lake ecosystem and providing constructive solutions.
20. The feasibility study on Urmia Lake salt industrial utilization considering environment aspects.
21. Feasibility study on new technologies application for the sake of Urmia Lake rescue.

V. Facilitate and increase of the water volume entering to the Lake throughout the structural measures

22. Water transfer from rivers to the lake.
23. Water transfer from Hasanloo Dam to islands and wetlands located in borders of Urmia Lake and opening the path of waterways feeding southern wetlands.

VI. Water Supply from new water resources

24. Appropriation of required funds and accelerate transferring water from Zaab river to ULB and Priority in implementing of Silveh water transfer project.
25. Transfer of ULB treated wastewater into Urmia the lake.
26. Study of water transfer project from Caspian Sea to the Urmia Lake.

27. The executive agencies are responsible to implement the approved projects and ULRP committee is only responsible to monitor the implementation process of those projects.

5.3. Method

To perform a qualitative assessment of the ULRP, this study elicited the opinions of selected experts with different backgrounds who are well aware of Urmia Lake situation. Among these experts were individuals from academia and government representatives with different backgrounds. The Expert opinions assessments followed by field observations during three field visits and related literature.

5.3.1. Expert Opinion Solicitation

To study the specific challenges and barriers which are driven from Urmia Lake complex situation, the survey targeted the experts who have substantial recorded work experiences or scientific publications related to the Urmia Lake. The first group of experts (n = 26) was selected by Research Division of Urmia Lake Restoration Program through their related experiences for Urmia Lake, who were approached in the roundtable discussion about the past, present and the future of Urmia Lake. The discussion was organized at Sharif University in Tehran, Iran in December 2014. Additional experts who had at least one related scientific publication about Urmia, were not present at the discussion at Sharif University, were approached by email (n = 14). In total 40 responses were gathered. Most of the experts had a background in water resources management (18), followed by agriculture (12), ecology (4), economic (2) and social sciences (3). Regarding the main affiliation, the experts were divided into two groups. Experts who work in public policy and/or governmental organizations were categorized as policy makers” (17) and experts who work at universities or research institutes (23) were categorized as “scientists”.

On the first day of the roundtable at Sharif University, the experts were given the 27 proposed measures under the ULRP and were asked to propose any additional measures they were missing. On the following day, a form was given to the 26 experts incorporating both the newly proposed measures and the existing ULRP measures (Supplementary Information 1). For each measure, experts chose between five different options: i) very strong; ii) strong; iii) medium; vi) weak; and v) very weak. The five-point scale, as follow: “i) very strong (100); ii) strong (75); iii) medium (50); vi) weak (25); and v) very weak (0), were used to calculate the mean and the standard deviation (SD) of the scores for each individual measure. The calculated mean for each measure was interpreted as the strength level of the experts’ general support for each measure and was used to rank the measures. The SD was interpreted the variation of the scores for each individual measure. The calculated means for each measure were interpreted as “strength level” of the experts’ general support for each measure, and were used to rank the measures. The SD was calculated to characterise the variation of the scores for each individual measure. To assess the prioritization of different categories, the mean and SD of different categories of measures were also presented. To show to what extent the experts (dis)agree for each measure and category the mean and SD of the score given by experts with different background and role also were presented. In addition, a Pearson correlation was used to determine the correlation coefficient between the experts’ opinions with different backgrounds[2].

5.3.2. Field visits

The field visits were done to interpret survey results as well as – by a set of anecdotic evidences, to further illustrate specific complexities and barriers to restore Urmia Lake. Three field visits have been conducted by the author on 10–12 January 2016, 10–12 April 2016, and 6–8 July 2016. The specific locations visited and documented by the author are shown in the Figures (5-1&2&3), respectively. All three field visits were facilitated by the ULRP committee and focused on the southern, south-western, and western parts of the basin, where 80% of the lake inflow originates. The visits included interviews with the local residents and authorities. The first field visit was followed by a presentation and discussion at the Urmia Lake Research Centre, Urmia University, Urmia (Figure 5-4-a), and a meeting with the local water authorities (Figure 5-4-b). The last two field visits were followed by roundtable discussions (Figure 5-4-c&d) with the ULRP committee members and advisors at the ULRP office, Sharif University, Tehran.

The visited spots in the three field visits can be clustered based on ULRP categories of measures as:

I. For the “Control and reduction of water depletion in the agricultural sector” category, the visited spots were:
   - The Miandoab irrigation network, which incorporates 60,000 hectares of irrigated land. Part of the area is to be transformed from furrow irrigation to pressurized irrigation at the request of farmers and with the acceptance of the regional official and ULRP committee. I conducted discussions with some of the farmers there about their visions and expectation of ULRP. I also visited a few specific places in the Miandoab area:
     - H32 farmland which is composed of 720 hectares of irrigated land growing mainly wheat, barley, and sugar beet. I accompanied representatives of the ULRP and the regional water

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[2] *The statistical analyses were done using Python, Jupyter notebook software and Pandas, Numpy, and SciPy libraries.*

    authority to listen to discussions with farmers regarding the financial support they had requested to change from furrow to sprinkler irrigation. I also visited the water distribution system efficiency office which is under the ministry of energy, and the water conveyance efficiency office, which is under the ministry of agriculture.

    - An apple farm, which had recently changed furrow to subsurface irrigation, where I interviewed the farmers.

II. For the “Control and reduction withdrawal of surface and groundwater resources in Urmia Lake Basin” category, the visited spot was:

- The farms between Bookan Dam and Nazloo Dike, where illegal water withdrawals from both surface and ground water have been extensively reported.

III. For the “Initiatives on Protection and mitigation of negative impacts” category , the visited spot was:

- Sources of dust in the southern areas of the lake, where the local planted local halophytes.

IV. For the “Studies and software measures” category, the visited spots were:

- Urmia Lake research center at Urmia University
- The Shahid Kalantari Causeway

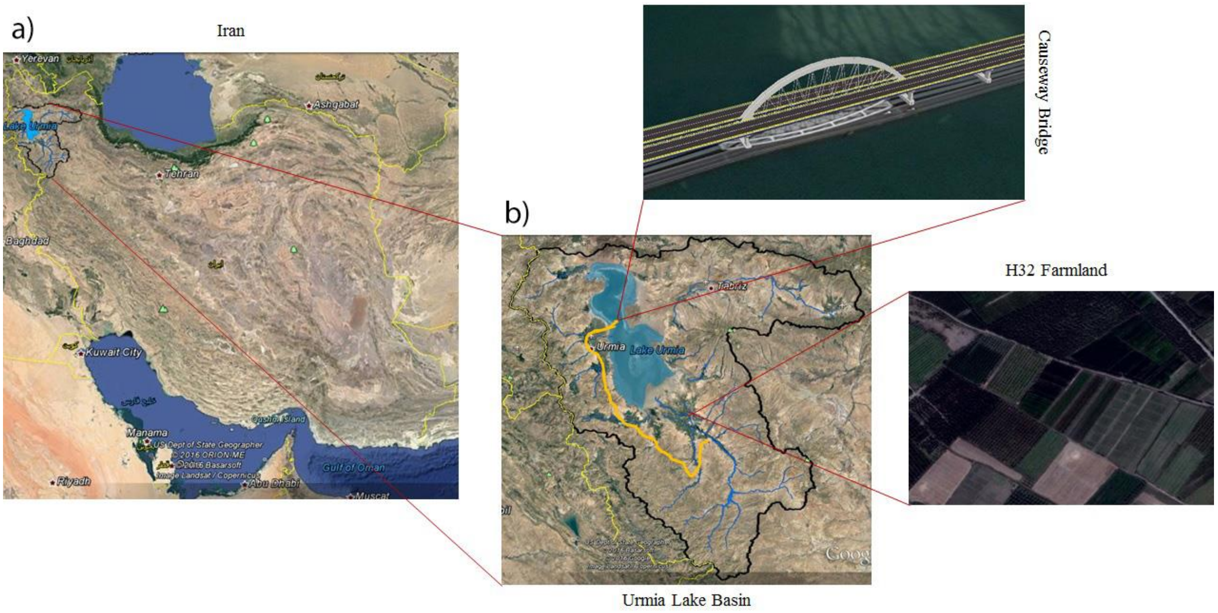


Figure 5-1 a) The location of Urmia basin in Iran b) the route of the first visit to the Urmia basin, and the main places visited

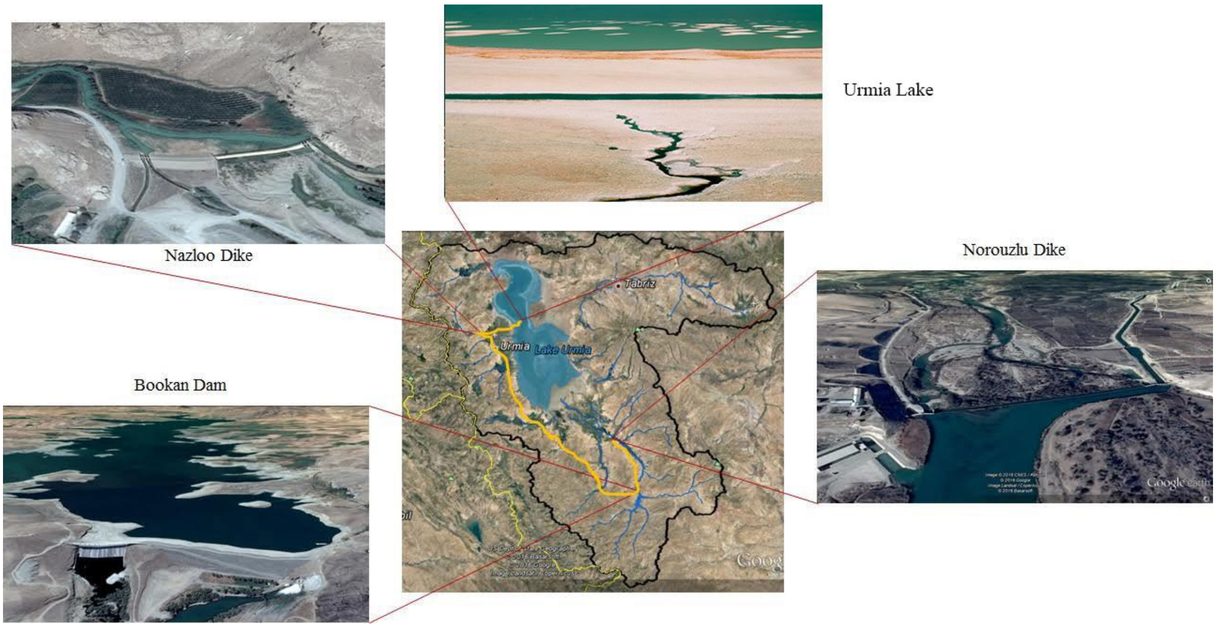


Figure 5-2 The route of the second visit to the Urmia basin, and the main places visited

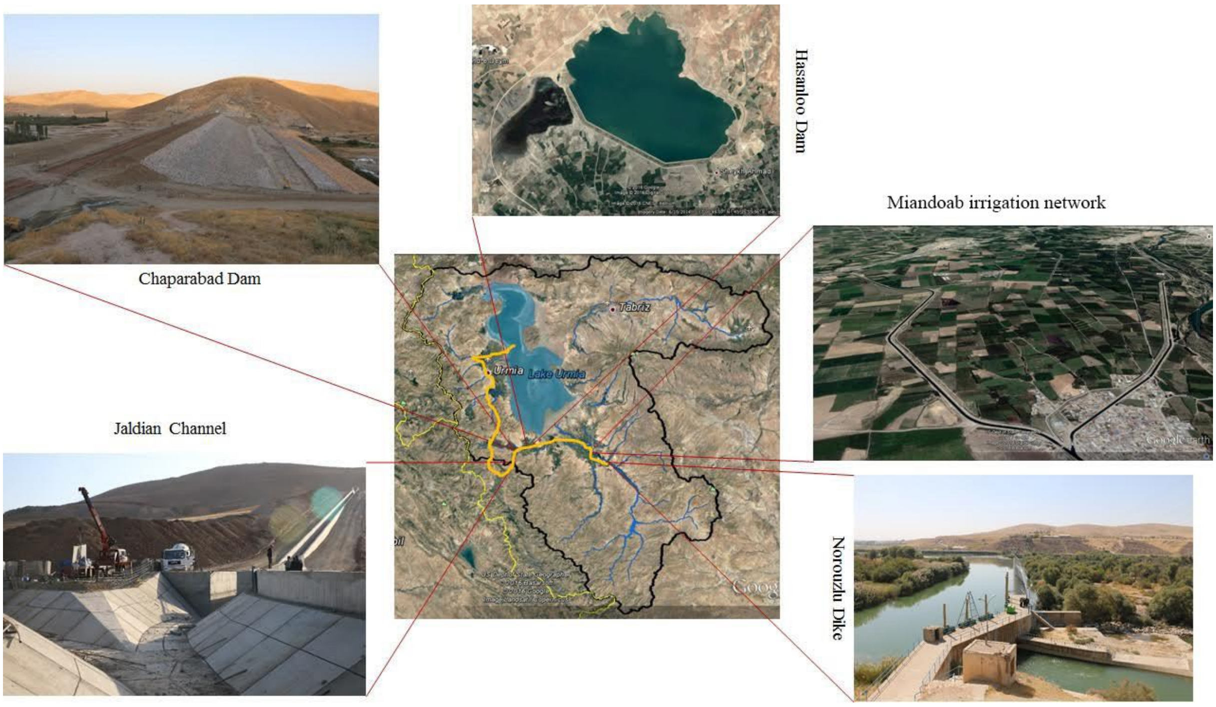


Figure 5-3 The route of the second visit to the Urmia basin, and the main places visited

V. For the “Facilitate and increase of the water volume entering to the Lake throughout the structural measures” category, the visited spots were:
  - The opening up and dredging of the Ajichai River, one of the rivers feeding Urmia Lake
  - Water release from Hasanloo Dam in the non-irrigation season

VI. For the “Water Supply from new water resources” category, the visited spots were:
  - The Jaldian Channel which will aim to transfer water from Zaab basin to Urmia basin.
  - The Chaparabad Dam which is intended to hold the water transferred from the Zaab basin and releases it during the non-irrigation season into the lake.

Figure 5-4 a) The presentation at the Urmia Lake Research Centre, Urmia University, Urmia, on 10 January 2016; b) With local water authorities in Urmia basin 10 April 2016; c) Roundtable discussion, ULRP office, Sharif University, Tehran, 12 April 2016; d) roundtable discussion, ULRP office, Sharif University, Tehran 8 July 2016. © ULRP

5.4. Results

The experts evaluated the URLP measures in two stages. In the first stage of the survey, experts were asked to propose new measures in addition to the ULRP measures. The following 10 measures were proposed by the experts:

1. Reduce water use in the agricultural sector by crop pattern change and increase irrigation efficiency (Category 1).
2. Rational pricing of water for agriculture on the basis of real value (Category 1).
3. Applied the plan for preventing slew (Category 1).
4. Allocating farmer’s water right based on volume rather than by duration (Category 1).
5. Establish Watershed Management Council with the participation of all interested parties and stakeholders (Category 5)

6. Prepare a comprehensive plan for water resources planning at the basin level (Category 5).
7. Develop a plan for adaptation to climate (Category 4).
8. Calculating the minimum Environmental Flow Requirement (EFR) and adjusting reservoirs operational rules to fulfill that (Category 4)
9. Develop action plan for wastewater treatment in standards rate and apply for alternatives usage like irrigation (Category 4)
10. Feasibility study of reducing the rate of evaporation from the lake (separation of the very small deep parts of the body of the lake in dry years) and evaluation of environmental impacts (Category 4).

Of the 10 alternative measures proposed by experts, four measures (numbered 1 to 4) are related to agricultural sectors (crop pattern change and increased irrigation efficiency, rational water pricing, slew prevention, and water delivery to farms); and three to planning (watershed management council, comprehensive water-resource planning, and adaption to climate change). The remaining three are more technical, aiming at EFR estimation, reuse of wastewater, and reducing evaporation from the lake surface. These 10 plus the 27 ULRP measures—in total 37 measures—were used for the questionnaire forms. The results derived from the 40 questionnaire forms are presented in Table 5-1.

Table 5-1 The ranking results (Mean, Standard Deviation (SD)) drove from experts' score to each measure regarding ULRP (highlighted) and other proposed measures to restore Lake Urmia.

Rank	**Measures**	**Mean**	**SD**
1	Reduce water use in the agricultural sector by crop pattern change and increase irrigation efficiency.	82.6	16.0
2	Establish Watershed Management Council with the participation of all interested parties and stakeholders.	81.7	16.8
3	Improvement the current conditions of wells in ULB throughout the installation of smart water volume counter to record and monitor withdrawal amount (in order to increase the river flow recharge to the lake).	80.3	17.0
4	Prohibition on any increases in withdrawals from the basin's water resources and prevent new development, especially in the agricultural sector.	77.8	18.4
5	Perform the necessary coordination with the judiciary in order to facilitate and accelerate the implementation of determining the duty of without permit wells law, especially wells affecting surface water.	74.4	17.2
6	Prepare a comprehensive plan for water resources planning at the basin level	73.1	18.9
7	Prevent the unauthorized withdrawals of surface water	72.6	18.4
8	Implement approved projects by the executive organizations, controlling and monitoring the implementation of the projects by the headquarters of the restoration of Urmia Lake.	68.0	13.4
9	Planning for enhancing productivity of 60% left amount water used in agriculture sector by Ministry of Jihad-e-Agriculture	67.3	12.7
10	Allocating farmer's water right based on volume rather than by duration	67.1	12.7

11	Identifying effective factors on feeding major rivers leading to the lake through watershed management in order to increase recharge rate from rivers to the lake	65.6	17.5
12	Conducting cadastral survey for ULB Lands	63.7	12.4
13	Calculating the lake minimum environmental water requirement and adjusting reservoirs operational rules to fulfill that	62.1	19.4
14	Establishment of research center of Urmia Lake by Environment Protection Organization	61.8	14.7
15	Develop a plan for adaptation to climate	61.1	21.6
16	Development and implementation of comprehensive training program, capacity building, awareness, and getting public and local community participation to illustrating the consequences of current critical situation and the necessity of reviving Urmia Lake	60.5	17.5
17	Develop action plan for wastewater treatment in standards rate and apply for alternatives usage	60.4	15.6
18	Allocating funds and supplying required technologies by the government to increase efficiency of remained water usage.	59.5	19.0
19	Water transfer from Hasanloo Dam to islands and wetlands located in borders of Urmia Lake and opening the path of waterways feeding southern wetlands.	59.4	16.5
20	Finding out the vulnerability of health, hygienic, social and environmental problems caused by Urmia Lake dry up, preparation and implementation of prevention programs reducing and preventing the likelihood risk effects.	58.1	13.0
21	Feasibility study on new technologies application for the sake of Urmia Lake rescue.	56.5	17.5
22	Design and implementation of a comprehensive decision support system in ULB.	54.7	15.7
23	Feasibility of reducing the rate of evaporation from the lake (separation of the very small deep parts of the body of lake in dry years) and evaluation of environmental impacts	53.7	15.0
24	Preparation of productive programs increasing alternative employment and livelihood by relevant organization.	53.4	16.9
25	Study and implementation of ecological protection program in Urmia National Park following environmental concerns.	53.3	12.7
26	Study and evaluation of Shahid Kalantary causeway effects on Urmia Lake ecosystem and providing constructive solutions.	51.2	17.6
27	Rational pricing of water for agriculture on the basis of real price	50.8	45.8
28	Reduction of 40% of surface and ground water rights by purchase, by Ministry of Energy.	50.1	37.5

29	Water transfer from rivers to the lake.	50.0	22.4
30	Transfer of ULB treated wastewater into Urmia the lake	47.2	20.3
31	Identification of halophyte species adopting well with ULB circumstances and preparation of program in order to planting selected species in the salt marshes area around the Urmia Lake.	45.1	22.5
32	Applied the plan for Preventing slew.	43.7	23.7
33	Identification of dust source and stabilizing them.	41.3	21.3
34	The feasibility study on Urmia Lake salt industrial utilization considering environment aspects.	38.8	16.8
35	Stop all the dam projects in the study and implementation plans (excluding Shahid Madani and Cheraghveis dams) and the irrigation systems and water supply projects of downstream in the Urmia lake catchment, storage and release of water in the Shahid Madani dam exclusively for Lake of Urmia.	38.1	19.4
36	Appropriation of required funds and accelerate transferring water from Zaab river to ULB and Priority in implementing of Silveh water transfer project.	33.1	29.3
37	Study the Transfer Water Project from Caspian sea to Urmia lake.	23.3	21.9

By considering score 50 was associated with medium support, the results showed that 25 measures out of 37 (considering the SD) had a high to medium support from the experts. The highest ranked measure to restore the lake according to the 40 Urmia lake experts was "Reduce water use in the agricultural sector by crop pattern change and increase irrigation efficiency", which was one of the non-URLP measures proposed by experts. In contrast, none of the existing ULRP agricultural measures (ULRP measures #1 to #3) were ranked in the top 10 in this survey. The second-ranked measure is also a non-URLP measure proposed by experts, "Establish Watershed Management Council with the participation of all interested parties and stakeholders".

The 10 highest ranked measures were mostly related to the "Control and reduction withdrawal" category, reflecting the existing issues with water use regulation and implementation in the area. The lowest ranked results involved larger structural measures promoted under the "Water Supply from new water resources" category, including new inter-basin and wastewater transfer.

The high standard deviations, in particular for measures #27 "Rational pricing of water for agriculture on the basis of real price" and 28 "Reduction of 40% of surface and ground water rights by purchase, by Ministry of Energy" and 36 "Appropriation of required funds and accelerate transferring water from Zaab river to ULB and Priority in implementing of Silveh water transfer project" indicate high disagreements between the experts for implementing these measures.

The ranking of the URLP six categories (Figure 5-5) showed a consecutive order of categories as below:

i) Control and reduction withdrawal of surface and groundwater resources;
ii) Facilitate and increase of the water volume entering to the Lake throughout the structural measures;
iii) Control and reduction of water depletion in agricultural sector
iv) Initiatives on Protection and mitigation of negative impacts;
v) Studies and software measures;
vi) Water supply from new water resources.

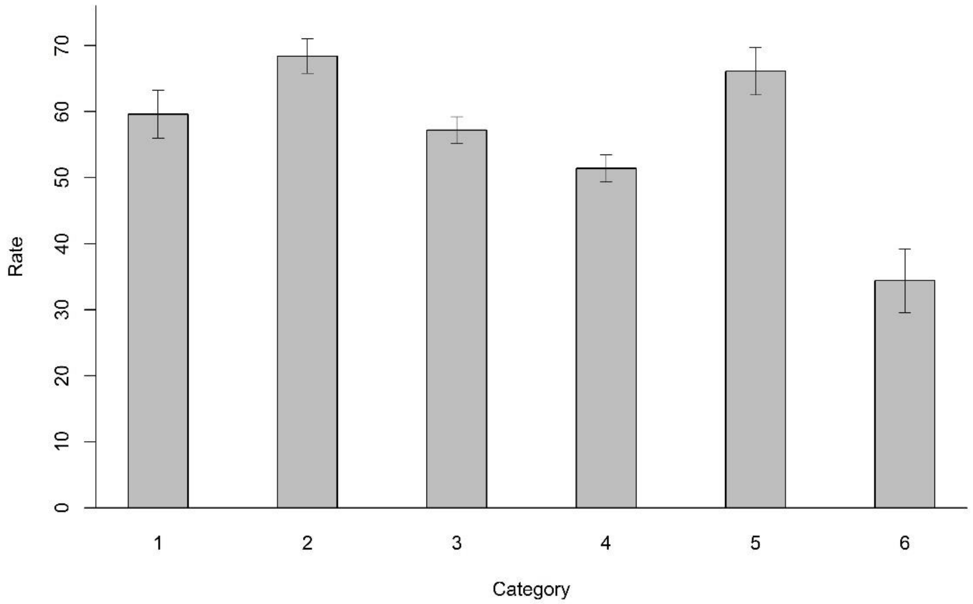
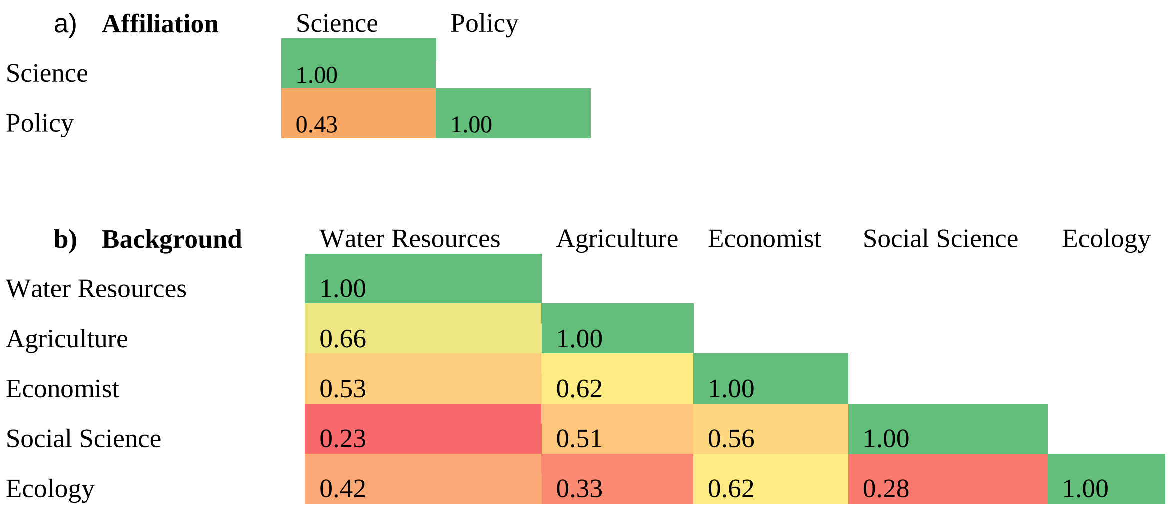


Figure 5-5 The result of ranking 6 ULRP packages based on the mean scores given by experts to the measures under each categories. The packages are: 1- Control and reduction of water depletion in agricultural sector, 2- Control and reduction withdrawal of surface and groundwater resources, 3-Initiatives on Protection and mitigation of negative impacts, 4- Studies and software measures, 5- Facilitate and increase of the water volume entering to the Lake throughout the structural measures, 6- Water Supply from new water resources.

The correlation analysis between people with different background and role showed in Figure 5-6. The results showed that there is quite a low correlation between experts' opinions from public policy and research sectors (Figure 5-6-a). The highest disagreement between these two groups was related to measures category 6 "Water Supply from new water resources" (Figure 5-7), and the highest agreement was about category 4 "Studies and software measures".

Regarding the experts' background, the highest correlation was between water resources management and agriculture groups (Figure 5-6-b). Furthermore, the lowest agreement was between water resources management experts and sociologist (Figure 5-6-b). The highest disagreement between experts' with different background reported for the category 6 "Water Supply from new water resources" (Figure 5-8) as well. The difference between the experts' opinions from different category about each measure presented in the Supplementary B, Table SI2-a and SI2-b.



a) **Affiliation**

	Science	Policy
Science	1.00	
Policy	0.43	1.00

b) **Background**

	Water Resources	Agriculture	Economist	Social Science	Ecology
Water Resources	1.00				
Agriculture	0.66	1.00			
Economist	0.53	0.62	1.00		
Social Science	0.23	0.51	0.56	1.00	
Ecology	0.42	0.33	0.62	0.28	1.00

Figure 5-6 a) The correlation between the experts' opinions from science and policy sector, b) correlation between experts' opinions with different background about Urmia Lake Restoration measures.

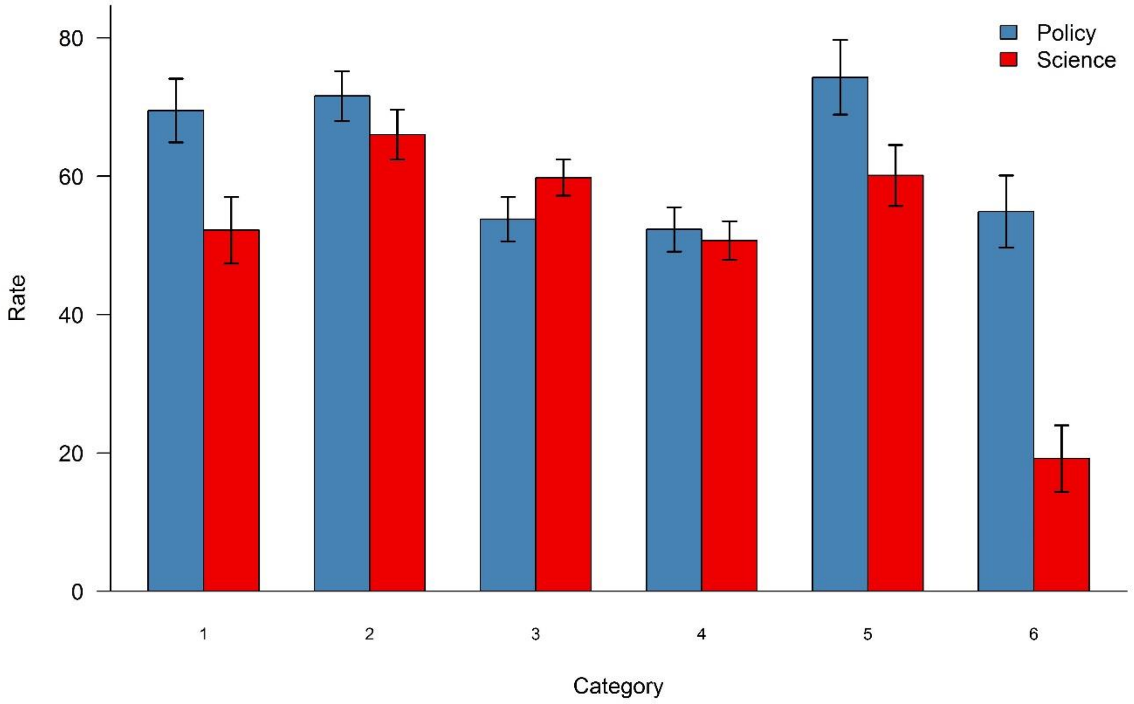


Figure 5-7 The mean scores given to six categories by experts who work in policy or science sectors, the error bars represent the standard error of the mean.

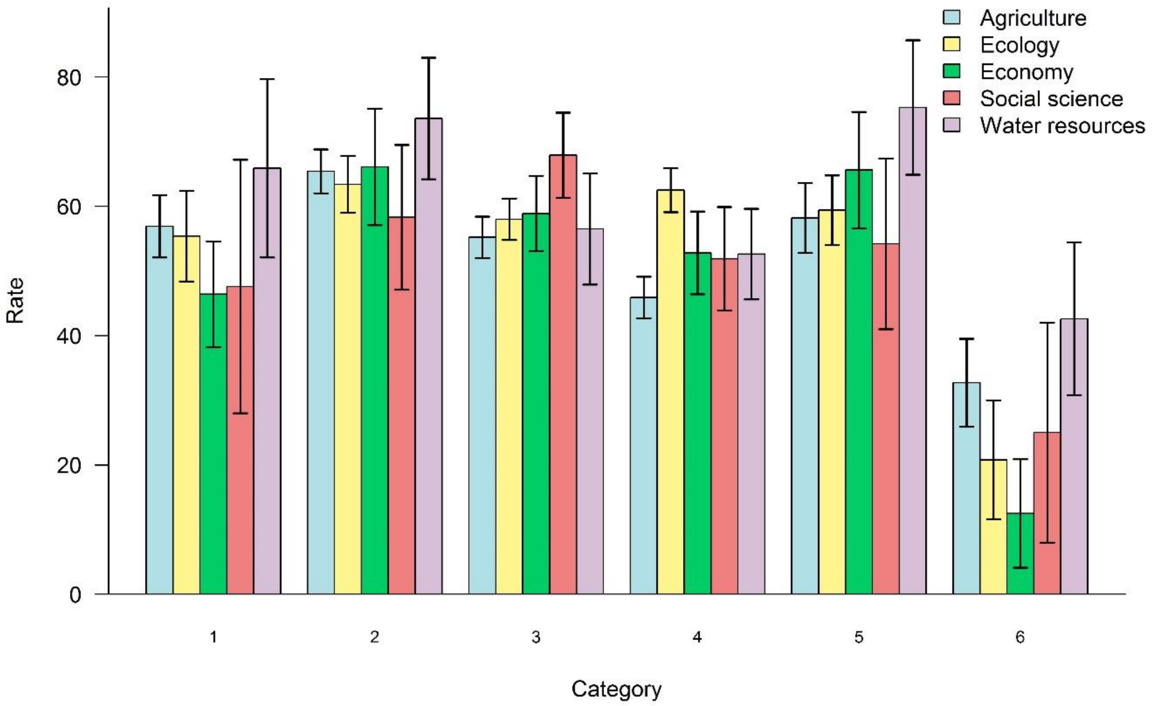


Figure 5-8 The average score of the six categories by experts with a different background, the error bars represent the standard error of the mean.

5.4.1. Field visit observations

Below is the summary of the field observations from the implementations and the potential challenges and barriers of Urmia Lake Restoration proposed measures:

I. *"Control and reduction of water depletion in the agricultural sector"* category:

- Currently, upon approval of the farmer's request, 15% of the project cost for a pressurized irrigation system will be paid by the farmers themselves while the remainder (85%) will be paid by the government (Agricultre, 2015).
- During my visit to farm H32 (Figure 5-9), I witnessed an argument between a ULRP representative and a group of farmers who owned furrow irrigation lands. The farmers claimed that some parts of the irrigation networks were not functional so they asked for financial support fortransformng the furrow to pressurized irrigation system. Upon close examinatim, however, we learned that with some technical correction the irrigation network could be functional again. On the other hand, we learnt that some consulting company approached farmers and encouraged them to receive a project approval and gave the project contract to them. The companies proposed not only pay the farmers back their 15% share, but also additional compensation. Regarding these issues, ULRP asked for an in-depth investigation before accepting/rejecting the farmers request.

Figure 5-9 Discussion and investigation regarding the famers’ request for a pressurized irrigation system in the H32 irrigated area (© ULRP)

- An owner of a 2.2 hectare apple farm in the south of the Urmia Lake basin changed his irrigation system from furrow to subsurface irrigation (Figure 5-10). The subsurface irrigation systems gave him the opportunity to precisely schedule both irrigation and fertilizer (fertigation). The first-year results showed that not only did water withdrawals decrease to one-sixth of the initial level, but apple production doubled. In response, he was intrested to extend his farm, so that his water use would be half the initial level and the rest kept for the environment.

Figure 5-10 An apple farm in south of Urmia Lake basin which changed furrow irrigation to subsurface irrigation; in the control room for the sub-surface irrigation (right), in the apple farm with the farmer (left) (© ULRP)

- A substantial part of water withdrawn returns to the surface derange in some part of the basin (Figure 5-11).

Figure 5-11 An irrigation canal (in the front) next to the drainage canals (in the back) in H32 Farmland, the farmers in this area indicated that normally half of the water withdraws

return to the deranges, which partially is used in downstream or goes to Urmia Lake. © Somayeh Shadkam

II. “Control and reduction withdrawal of surface and groundwater resources in Urmia Lake Basin”

- The committee representative indicated that one of the main barrier for controlling illegal groundwater extraction is overlapping responsibilities of authorities. There are more than one authorities are able to seal also un-seal the unauthorized wells which make it complex to control the illegal withdrawals.
- The unauthorized withdrawal of surface water is also a major problem (Figure 5-12).

Figure 5-12 unauthorized surface water withdrawals in Urmia basin. © ULRP

III. “Initiatives on Protection and mitigation of negative impacts” category:

- The farmers’ most-heard complaint is about their income; while, there is a considerable amount of wasted of harvested agricultural product (Figure 5-13).

Figure 5-13 the farmers of Jabal village complained that they cannot sell their product (left), © ULRP. The apples on the road waiting for the fruit dealer in a very cheap price (right), © Somayeh Shadkam

- There is a serious health problem regarding the salt storm in the basin (Figure 5-14). For "Studies and software measures" category.
- The local interviews highlighted the lack of awareness about the consequences of the lake desiccation in their life, as well as about the important role that farmers can play to rescue the lake. Many farmers believed that it is the job of the government to rescue the lake. Hence, promoting public awareness can increase people's motivation to support the ULRP. After some training courses, for example, people in Khas-e-Loo village planted local halophyte in the lake bed which helped to prevent salt storm (Figure 5-15).

Figure 5-14 Dust and salt storm in Urmia basin (right), a school girl affected breathing problem from dust. © ULRP

Figure 5-15 Training course for Urmia basin farmers (right), the volunteer work of Khas-e-Loo villages to plant local halophyte in Urmia Lake bed. © ULRP

For "Facilitate and increase of the water volume entering to the Lake throughout the structural measures" category

- Opening and dredging Ajichai River as one of feeding rivers for the Urmia Lake has been done.

IV. For "Water Supply from new water resources" category

- The water transfer Silveh canal was completed from 100%. The water transfer canal from Zaab was completed by 30% (ULRP, 2016).

Figure 5-16 Right Jaldian channel to transfer water from Zaab Basin to Urmia Basin. Left Chaparabad dam which is supposed to keep the transferred water from Zaab and release it in none irrigation season to reach the lake. © Somayeh Shadkam

5.5. Discussion

In general, the Urmia Lake experts supported appropriate implementation of existing regulations related to water use and development; at the same time, they less supported large infrastructure engineering interventions such as inter-basin water transfers as less effective. However, there was a considerable disagreement between policy makers and scientist for such an intervention. The scientist gave a quite low score to this category compared with the policy makers. Demand side measures such as crop pattern changes, irrigation efficiency improvements also ranked high, as opposed to supply-side measures. However, there is a considerable disagreement between the experts with agriculture and ecology backgrounds and social science backgrounds in this matter. Instead, the experts with social science background gave a higher score to supporting health, hygienic, social and environmental problems also increasing alternative employment and livelihood.

The field visit revealed some hidden barriers for implementation of ULRP. Firstly, saving water through ULRP agricultural measures may not be as straightforward as expected. There is some evidence that allocating funds to increase efficiency can encourage some fraudulent behaviour in the basin. In addition, there is a possibility that higher efficiency encourages the farmers to expand irrigated land and consequently increase water depletion, especially due to the high return flow rate in the basin. The field visit also revealed that controlling illegal water withdraw can be very challenging for both surface and groundwater. In addition, the farmers' complaints about their income and also the high rate of wasted products in some parts of the basin show that the basin value chain needs an improvement. A successful experience in Khaseloo village showed that promoting public awareness can increase people's motivation to support the ULRP. In addition, it is observed that the structural measures successfully helped to reduce evaporation.

The first top-ranked measure to restore the lake according to the 40 Urmia lake experts was "*Reduce water use in agricultural sector by crop pattern change and increase irrigation efficiency*," which was one of the non-URLP measures proposed by experts. This measure got quite a high score from all experts with different backgrounds. However, none of the existing ULRP agricultural measures (ULRP measures #1 to #3) were ranked in the top ten of this survey. This shows that the existing URLP measures in the agricultural sector are perceived insufficient, according to expert opinions.

Among the existing ULRP agricultural measures, "Reduction of 40% allocated ground and surface water to the farmers through direct purchasing system by Ministry of Energy in five-year period," ranked 30th of 40 options. Experts assessed this measure relatively low, as the direct purchasing of water rights from farmers could have considerable social impacts (Berbel et al., 2015). Moreover, due to a very high rate of illegal water withdrawals in the basin (ULRP, 2016b), there is a major risk that the water purchased might not reach the lake.

Another ULRP agricultural measure, "*Allocating funds and supplying required technologies by government to increase efficiency of remained water usage"* ranked 20th. This relatively low ranking is due to a number of issues that are identified in the existing literature. In Chapter 4 of this theses we show that an increase in irrigation efficiency in the Urmia basin may accelerate water depletion, due to decreasing return flow, which is quite high in some parts of it as noticed in the field visit. This type of unintended consequence is known as the rebound effect (Berbel et al., 2015) and can contribute to an underlying imbalance of water demand and withdrawals in the basin.

Another reason why this option received low expert ranking is the potential for fraud in allocating government money to improve irrigation efficiency as observed in the field visit. These local issues would likely have contributed to the experts' perceived low ranking of "*Allocating funds and supplying required technologies by government.*" Given the complexity of local practices, including the potential for fraudulent behavior, a detailed assessment is recommended before implementing new irrigation technologies in the field.

Another important cause for concern in implementing irrigation efficiency-improvement policies is that increases in water availability (due to higher irrigation efficiency) are highly likely to encourage farmers to increase the irrigated land area as observed in the field visit. In most cases, farmers are unaware of the depletion and increased scarcity of water due to the reduced return flows of efficient irrigation systems.

The second-ranked measure is also a non-URLP measure proposed by experts, "*Establish Watershed Management Council with the participation of all interested parties and stakeholders*." There is quite a high level of agreement between experts to support this measure. The water-resource management requires a radical reorientation and an effective dialogue among decision makers, stakeholders, and engineers/academics (Falkenmark et al., 2004). For effective water-resource management, a tripartite alliance between policymaker, stakeholder, and engineer (scientist) is required (Morsing and Schultz, 2006). Simonovic and Bender (1996) concluded that participation is essential because stakeholders have the knowledge and experience necessary to formulate effective alternatives. The policymaking process should ideally be participatory, as policy decisions are based on societal values as a whole (Stave, 2002). Thus, on this basis, all stakeholders should be given a voice and be heard without prejudice and advantage (Hampton, 1999) and should be involved in discussing the trade-offs (Hashemi, 2011). Stakeholders will learn from each other and make decisions based on their evolving understandings and perspectives. In addition, the involvement of stakeholders in decision making will bring more support to the plan from their side. The inclusion, and perceived high ranking, of this measure reflects the experts' opinion that the lack of a participatory approach will hinder the effective implementation of the ULRP.

The 10 highest-ranked measures were mainly related to the "*Control and reduction withdrawal*" category, reflecting the existing issues with water-use regulation and implementation in the area. Figure 4-3 shows the locations of wells for groundwater withdrawals in the Urmia basin. There are around 88,000 wells in the Urmia Lake basin, of which an estimated 40,000 are unregistered (ULRP, 2016a). The current water governance in the basin probably makes it difficult to prevent illegal extraction as observed in the field visit. The unauthorized withdrawal of surface water is also a major problem as observed in the field visit. The expert opinions from the survey confirmed by Berbel et al.

(2015). Based on a comprehensive literature review covering theoretical and empirical studies of water savings, water diversion, and water depletion, they concluded that there are three key conditions for success in a water-saving plan: i) strict limitations placed on the size of the irrigated area; ii) the reduction of former water rights; and iii) the reassignment of water savings to achieve environmental goals.

The lowest-ranked results involved larger structural measures promoted under the *"Water supply from new water resources"* category, including new inter-basin and wastewater transfer. However, there was a high level of disagreement, in particular between scientist and policy makers, towards this measure. Under the water transfer project from the Zaab to the Urmia basins, it is planned to transfer $690\times10^9 m^3 yr^{-1}$. The results of Chapter 4 of this paper show that such technical measures can be the most effective in quantitative terms. An inter-basin transfer has been defined as "the transfer of water from one geographically distinct river catchment, or basin to another, or from one river reach to another." Note that this definition includes intra-basin transfers (Gupta and van der Zaag, 2008). Despite scientific uncertainty, huge economic costs, and potentially large environmental impacts, because of the interlocking nexus between engineers, politicians and financiers, inter-basin water transfer seems to be the increasingly dominant solution all around the world (Dyrnes and Vatn, 2005). Inter-basin transfers currently divert about $540\times10^9 m^3 yr^{-1}$ of water, which represents approximately 14% of all global water withdrawals. There are proposed schemes that will transfer an additional 940 $\times10^9 m^3 yr^{-1}$ from basins. If these plans were implemented, inter-basin transfer would represent more than a quarter of all water withdrawals by the year 2025 (Vijayan and Schultz, 2007). However, there is an inherent tension between the laudable principles of IWRM and sustainable development, on the one hand, and large hydraulic infrastructural works on the other. Gupta and van der Zaag (2008) assessed whether inter-basin transfers were compatible with integrated water-resource management by reviewing five inter-basin transfer projects worldwide. The results indicated that such transfers do not easily align with the values of equity, ecological integrity, and economic efficiency that underpin IWRM.

Moreover, as discussed in Chapter 4 of this thesis, transferring wastewater to the lake may place additional pressure on groundwater resources in the basin, as wastewater was previously used for groundwater recharge prior to the ULRP implementation.

The ranking of the six URLP categories: Figure 5-5 showed that mainly categories, "*Control and reduction withdrawal of surface and groundwater resources*," "*Control and reduction of water depletion in agricultural sector*," discussed above, together with "*Facilitate and increase of the water volume entering to the Lake through structural measures."* can play key roles for in making the plan a success. *Structural measures* category can play an important role in the Urmia basin because of its ability to considerably decrease evaporation as observed in the field visit. The next category is "*Initiatives on protection and mitigation of negative impact*." Although this category did not receive a high ranking and is unlikely to have a significant impact on the inflow, it could nevertheless be important because of its relationship with public health. Recently, a survey regarding the epidemiology of diseases from dust was conducted by the Lake Urmia Committee. The research assessed the impacts of dust on the lungs of schoolchildren including 88 students in three neighboring schools. The results reported that 3% had asthma, 21% noisy breathing, 30% dry cough, and 10% breathing problems while sleeping (ULRP, 2017). The next ranked category is "Studies and software measures". The highest measures in the research and study category is "Development and implementation of comprehensive training program, capacity building, awareness, and encouraging public and local community participation to illustrate the consequences of the currently critical situation and the necessity of reviving Urmia Lake." This measure is supported mostly by experts with social science background. The field visit revealed that promoting public awareness can increase people's motivation to support the ULRP.

Among **measures proposed by experts**, "*Allocating farmers' water rights based on volume rather than by duration*" was the highest ranked (13). Current water delivery in the basin is based on counting, with each farmer being permitted to withdraw water "n" times per month. Discussion with farmers showed that because the amount of water used by each farm is unclear, many conflicts arise. The next measure is "*Calculating the lake minimum environmental water requirement and adjusting reservoirs operational rules to fulfil that,*" which ranked 15th. Abbaspour and Nazaridoust (2007) estimated the Urmia Lake EFRs to be around $3100 \times 10^6 m^3$ which has been defined as the ULRP target (ULRP, 2016b). The study is based on the assumption that 240 (g/l) NaCl is the threshold that the *Atemia urmiuana* can tolerate. However, Agh (2007) reported the negative impact on survival, growth, and reproductive level of *Artemia urmania* at salinity levels ranging from 75 to 175g/l in a 23-day long experiment. Higher salt concentration were not tested, but analyses of other species of *Artemia* reported no survival above 230 g/l (Browne and Hoopes, 1990).

Moreover, due to the reduction in lake volume since 1995, the salinity of its water has increased sharply, causing about eight billion tons of salt to collect in the deeper parts of the lake. A recent investigation by ULRP revealed that the depth of the deepest part of the lake reduced from 16m to only 2m over the 1995–2015 period. Although the overall fall in Lake water level was only around 7m, a 7m layer of salt has accumulated in the deeper parts of the lake. The ratio of the area to the volume (m^2/m^3) has thus increased considerably (i.e., for the same volume of water, higher evaporation is expected). In Chapter 3, we estimated the hydrological EFRs around $3.7 \times 10^6 m^3$. However, as the experts proposed, an in-depth study is needed to review the Urmia Lake environmental flow requirement. Strict regulations are also needed to monitor the operational rules of reservoirs to ensure they release the required amount of water.

The "*Develop a plan for adaptation to climate*" measure was ranked 17th. The results of the third chapter of this theses showed that water availability in the Urmia basin will likely decrease considerably due to climate change and that water-resource management plans for the basin are not robust to climate change. Therefore, an adaptation plan that takes into account a changing future climate is necessary. The next top-ranked measure among the experts is *"Develop action plan for wastewater treatment in standards rate and apply for alternatives usage"* whereas ULRP suggested directing the wastewater straight into the lake. The wastewater measures proposed by experts have less of an environmental impact, as the wastewater can still return to the environment as return flow and join the groundwater, while ULRP measures put greater pressure on groundwater (please refer to Chapter 4).

The "Feasibility of reducing the rate of evaporation from the lake (separation of the very small deep parts of the body of lake in dry years) and evaluation of environmental impacts" measure was ranked 23rd. Hassanzadeh et al. (2012) showed that the main reason for the shrinkage of Urmia Lake was decreasing inflow. It is probably therefore wiser to invest in measures to increase inflow rather than looking to reduce evaporation rate.

The "*Rational pricing of water for agriculture on the basis of real value*" measure received a low ranking of 27th. Many authors have argued that water pricing is useless where water has a higher value and that farmers adapt to deficit irrigation due to the structural scarcity of the region (e.g. (Berbel et al., 2015, Gomez and Gutierrez, 2011, De Fraiture and Perry, 2002). In the Urmia basin the water costs are heavily subsidized and consequently, water is too cheap (ULRP, 2015b). More in-depth research is needed to deal with this issue.

The experts' opinion and field visits both highlighted two following issues. Firstly, the existing agricultural URLP measures in the agricultural sector may not be as effective as expected. The ULRP measures received relatively low ranked, also the field visit revealed some serious challenges in implementing the measures. Secondly, implementation of "Control and reduction withdrawal" package which includes prevention of new projects and unauthorized surface water withdrawal, also the implementation of the law for illegal wells is a very critical category and need especial attention. On the other hand, the "...transferring water from Zaab river to ULB and Priority in implementing of Silveh water transfer project" measures which received the very low ranked by the experts; while, it was one the most advanced measure in terms of implementations (Silveh 100% and Zaab 30% progress) despite considerably high expenses. This can be explained by high level of disagreements between scientist and policy makers regard this measure.

5.5.1. Limitations of the study and of the interpretation of the research results

Although the method applied in this study is designed to be comprehensive enough to identify the challenges and hidden barriers of the ULRP, there were some limitations which deserve attention. First, the linguistic uncertainty in the statement put to experts, and also in the description of the ULRP measures, which may have affected the responses given. This linguistic uncertainty can be classified into three types: ambiguity, under-specificity, and vagueness (Knol et al., 2010). Linguistic ambiguity occurs when words can have more than one meaning and it is uncertain which meaning is meant (Knol et al., 2010). For instance, "reduction in water use" can be interpreted as "reduction in water withdrawals" or "reduction in water depletion." Under- specificity arises when too much room for interpretation mostly in the absent of adequate details (Knol et al., 2010). To explore the general supports of Urmia Lake experts toward each measure, the experts were asked to score the measures to restore the lake with no specified aspect. Therefore, there might be different interpretation about what "restore the lake" actually mean among them. Therefore, a further study is suggested to use multi-criteria ranking considering different aspects and criteria to Urmia Lake restoration. In addition, the measures proposed by experts, which were added to the survey, have some overlap with the ULRP measures. This may be because the experts believed that the ULRP measures, though targeted at the right issue, may be insufficient. However, interpreting how proposed measures might overlap could pose difficulties. Furthermore, as the survey was done only a few months after the implementation of ULRP had begun, the implementation of some measures may have been unclear to the ULRP committee and executive team. Such ambiguity was unavoidable in the survey. At the same time, common experience and discussion can reduce the level of these type of uncertainties (Simonin, 1999). All experts involved in the survey have some experience regarding Urmia Lake. The first expert group attended the first day of the roundtable where they had intensive discussions about ULRP and its challenges. The rest of the experts have at least one peer-reviewed paper about Urmia Lake. These factors could help to reduce the level of ambiguity (Simonin, 1999) and are also likely to reduce the level of linguistic uncertainty. In addition, the results of this survey are representative only of a selected group of highly informed experts about Urmia Lake with different backgrounds and interests. Therefore, an advance analysis to outline an proper sample distribution and other statistical properties describing experts can give a better inside of general expert opinions (Biesbroek et al., 2013), and this is recommended for future studies.

The field visits were aimed at investigating the hidden challenges of and barriers to restore Urmia Lake, and I used an unstructured interview, with open-ended questions, where I identified the local issues being raised and looked for different points of view among the actors involved in the discussions. While this type of interview method has an advantage in terms of revealing in-depth views on a particular topic, a further study could use a more structured interview with stakeholders to systematically validate some of the conclusions drawn in this study.

5.6. Conclusions and future outlook

To perform a comprehensive assessment of a water-saving intervention, a combination of quantitative and qualitative approaches is needed. Following the technical assessment of the quantifiable ULRP measures implemented in the previous chapters, this chapter asked 40 experts their general support regarding the ULRP measures, which was complemented by local field observations. The results showed that most experts supported demand-oriented measures such as regulations to control and reduce withdrawal of surface and groundwater resources. The experts also indicated the need to revise the ULRP agricultural measures on controlling agricultural water demand by instead adopting measures such as crop pattern changes and targeted irrigation efficiency improvements. However, controlling water withdrawal may pose a serious challenge, including a rebound effect. The experts also recommended a gradual reduction in the amount of irrigated land to be implemented under the authority of Watershed Management Council with the participation of all interested parties and stakeholders. In general policy makers and scientist have a quite low agreement to support the measures, in particular about the large scale engineering interventions such as inter-basin water transfers. This can be a serious issue for the possible failure of ULRP and call for a better mutual understanding between policy makers and scientist in this matter.

In general, water supply-oriented measures such as inter-basin water transfers are seen as the least supported measures. This is surprising, as the quantitative assessment showed that water supply–oriented measures would not only increase inflow to the lake the most, but that the success of ULRP also depends on them. This calls for revising the ULRP so that supported measures by experts can have a greater quantitative effect. However, in the third chapter of this thesis we showed that the water availability of the basin will likely decrease due to climate change. Therefore, water supply–oriented measures should be taken into account—in the most sustainable way, however, and with due consideration of equity, ecological integrity, and economic efficiency. Another option is to restore the lake partially by reducing its surface area (to reduce evaporation loss) until more water becomes available (UNDP, 2014). The plan should be tailored to the various stages of climate change impacts and water availability conditions and should include the balancing of demands for irrigation, ecosystem preservation, and social and human impacts. It should also operate within national and regional geopolitical realities.

CHAPTER 6:
Synthesis

CHAPTER 6:

Synthesis

6.1. Introduction

To supply food and energy for growing populations humans have developed reservoirs and extract water for irrigation (Biemans et al., 2011). Furthermore, climate change has a significant impact on the natural hydrological cycle and amplifies water scarcity in (semi)-arid regions (Haddeland et al., 2014, Fernandes et al., 2011, Santos et al., 2014). Thus, water volumes reaching downstream lakes and wetlands are considerably reduced, resulting in severe environmental, social and economic impacts. These conditions are likely to get worse due to climatic changes (Haddeland et al., 2014). Therefore, to save natural resources water-saving interventions have been introduced to the environmental policy agenda in many (semi)-arid regions. Many policies, however, have failed to reach their objectives to increase water availability for the environment. These complex challenges call for an urgent and comprehensive assessment, in particular for highly endangered ecosystems, on how climate and anthropogenic changes will affect required environmental flows and on how water-saving policies can effectively deal with those future changes. This thesis, therefore, assesses climate and anthropogenic changes on reducing environmental flow requirement of Urmia Lake, a highly degraded hyper-saline lake in north-western Iran. In addition, the thesis assesses the effectiveness of policies aiming to restore and preserve the Lake.

To address these objectives, four research questions were defined (Chapter 1) and addressed (Chapter 2-6). The first research question was defined as: “*What are the combined and discrete effects of climate variability and change, and water resources development on Urmia Lake inflow?”* To answer this question I regionalized, calibrated and applied the Variable Infiltration Capacity (VIC) model irrigation and reservoirs modules to the Urmia basin. I estimated the relative contributions of climate change and water resources development - which includes construction of reservoirs and expansion of irrigated areas - to changes in Urmia Lake inflow over the period 1960-2010 (Chapter 2). Then, the model was forced with bias-corrected climate model outputs for both a low (RCP2.6) and a high (RCP8.5) greenhouse-gas concentration scenario to estimate future water availability and impacts of water management strategies (Chapter 3). The second question was defined as “*How is it possible to preserve Urmia Lake under future climate change and water resources development?* To answer this question, I first estimated Urmia Lake Environmental Flow Requirements (EFR) by adapting the mean monthly flow method for hypersaline lakes. The estimated monthly and annual EFR were compared with simulated inflow derived from VIC irrigation and reservoirs modules under different climate change and agricultural water resources management scenarios to evaluate how and in which scenarios the lake can be preserved (Chapter 3). The third question was defined as: “*What is the expected quantitative impact of ULRP on Urmia Lake inflow?”* To answer this question, I introduced a constructive framework to assess the water-saving interventions by estimating five components: 1) *Total water demand* under socioeconomic scenarios, *2) Water supply* under climate change scenarios, 3) *Water withdrawal* for different sectors, 4) *Water depletion* and 5) *Environmental flow*. The framework includes climate change and socioeconomic scenarios and recognition of total water demand and water withdrawals; also, water withdrawals and water depletion. This framework was applied to assess ULRP under different climate change and socioeconomic scenarios (Chapter 4). The fourth question was defined as "*To what extent are ULRP measures effective and what the implementation challenges are?"* To answer this question, I used a qualitative approach. Two types of qualitative data were used and discussed further. First, the 40 experts' opinions were used to score ULRP measures. Second, the results were analyzed and discussed based on my observations from ULRP implementation.

In the next section of this chapter, the four research questions and results are discussed followed by a discussion on implications of the thesis results for the Urmia Lake Restoration Program (Section 6.2). The next section extensively discusses the impacts of the results of this study for defining a sustainable approach to preserve Urmia Lake (Section 6.3). The contributions of this thesis to water management science and policy are discussed in Section 6.4 and this chapter ends with a reflection on methods used in this thesis and some direction of future research in Section 6.5.

6.2. Discussion of main results

6.2.1. Impact of climate variability and change, and water resources developments on Urmia lake inflow (Q1)

While climate variability and change and water resources development are identified as the main drivers for Urmia Lake desiccation, (Farokhnia and Morid, 2014, Fathian et al., 2014, Hashemi, 2011, Hassanzadeh et al., 2012, Jalili et al., 2015, Zeinoddini et al., 2009), the relative contributions of these two drivers had not been quantified. It was therefore not clear to what extent climate change and water resources development have contributed to the declining inflow, which makes it difficult to develop a plan to preserve the lake from further environmental degradation. Therefore, in the first step of the thesis, the role of each influential factor on Urmia Lake inflow was assessed.

Impact of climate variability and change on Urmia Lake inflow

The trend in simulated naturalized river flow showed a decreasing pattern similar to precipitation. However, the relative decrease in naturalized flows was much higher than the change in precipitation (Chapter 2). This is caused by a relatively low runoff coefficient which makes the basin vulnerable to fluctuation in precipitation. Furthermore, the seasonal and inter-annual variability of precipitation have also changed significantly over the last two decades (Delju et al., 2013) and less rainy days have been reported (Arkian et al., 2016). These longer dry periods encouraged increased anthropogenic water extraction. To reduce the vulnerability to changes in precipitation more flexibility in land and water management (Siderius, 2015) should be considered in the lake restoration plans. For example, by providing more water supply in a dry period, to prevent people from using environmental flow, or changing cropping patterns to adapt to the longer dry periods. In addition, climate variability has also not been considered in EFRs estimation. In Chapter 3 an EFRs method was developed taking into account the intra-annual climate variability.

The results of the climate change impact assessment showed that the effects of climate change are likely to continue in the future (Chapter 3). The current trend of reducing rainfall and run-off is probably part of a long-term change in the climate in this area. These results are consistent with those presented in the IPCC reports which showed a decline in runoff for this region for both the near-term (Kirtman, 2013) and long-term future (Collins, 2013).

Impact of reservoirs development on Urmia Lake inflow

The results of Chapter 2 showed that reservoirs operation only have a limited direct impact on the average inflow into the lake. Most of the reservoirs, however, were built to supply water for irrigation projects. The effect of reservoirs should not be assessed in terms of operation, but in combination with the accelerating development of irrigated agriculture in the basin. Reservoirs can have both positive and negative indirect impacts on inflow. Reservoirs could potentially increase streamflow in dry periods by releasing water stored during wet periods. On the other hand, the reservoirs can cause a decrease in flow by providing additional water for irrigation (Chapter 2). Model simulation results indicate that during dry years reservoirs can cause an increase in flow into Urmia Lake. This indicates the potential role of reservoirs in water management in times of water scarcity. On the other hand, the highest lake EFRs deficit will be from April to June (Chapter 3). Therefore, reservoirs can have a role in seasonal water management over the year. Reservoirs can store water in the previous year and release it when the lake is in the highest need or/and a none-irrigation season. The seasonal management of the reservoirs is currently part of Urmia Lake Restoration Program (none-irrigation month in the basin) and had a visible impact on the lake surface area (ULRP, 2016). This indicates that reservoir management could potentially play a bigger role in the ULRP.

Impact of irrigation expansion on Urmia Lake inflow

The results showed that irrigation increased pressure on the basin’s water balance, especially during dry years. Furthermore, during the summer, there is a serious shortage in relation to meeting the irrigation water requirements from surface water increasing the pressure on other water resources such as groundwater (Chapter 2). These results showed the important role of reducing irrigation water use to prevent the lake from further degradation. Furthermore, reduction in irrigation water use was identified as the most feasible measure to restore the lake (Chapter 5); it is not a straightforward process and may not get the expected results (Chapter 4) and even may increase water depletion from the basin. Therefore, regarding the urgent situation of the lake along with measures to reduce irrigation water use, it is recommended to reduce irrigated land and reduce the agriculture sector in general.

Climate variabilities and change, reservoirs and irrigation combined impact

The results showed that climate change was the main contributor to the inflow reduction; however, the water resources development had a substantial additive effect on the inflow reduction. The findings support other studies that have indicated that a combination of climate change and water resources development have caused the lake degradation (Jalili et al., 2015, Fathian et al., 2014, Farokhnia and Morid, 2014, Hassanzadeh et al., 2012, Zeinoddini et al., 2009). In contrast, AghaKouchak et al., (2015) suggested that anthropogenic water extraction is the main reason for the lake shrinkage. One explanation can be the difference between satellite-based data, used in their study, and meteorological WFD/EI data used. However, their results are only based on assessing the basin Standardized Precipitation Index; while this study assessed the combined effect of climate variabilities and change, irrigation, and reservoirs on simulated inflow to the lake. The results of this study confirm the results obtained by Farokhnia (2015) who compared the impact of climate change and anthropogenic water use on Urmia Lake inflow with three different methods. His results indicated that climate change was the dominating reason (up to 72%) to reduce the lake inflow.

The impacts of different irrigation strategies were more visible under the low concentration scenario (RCP2.6) than under the high concentration scenario (RCP8.5), showing that proposed water management plans are not robust under climate change in this region (Chapter 3). This indicated that irrigation management plans in the basin should take climate change uncertainties into consideration. In addition, regarding a drier future and increasing water demand in the region, an urgent action in both regional (to limit anthropogenic impact) and global scale (to limit greenhouse-gas concentration) is needed to save the lake.

6.2.2. Preserving Urmia Lake under climate change and water resources development (Q2)

The results indicated that without climate change, the inflow would have been sufficient to meet the lake EFRs (Chapter 3). The results showed that if future climate change is limited assuming rapid and large-scale mitigation measures (RCP2.6) inflow can just meet the EFRs for the limited irrigation management plan. In this case, implementing the limited irrigation plan should become a priority. However, this is not the case for the high/rapid concentration scenario and also other water resources plans. Under more rapid climate change scenarios (RCP8.5) limited irrigation might be effective in short-term, but would be insufficient in the long-term, so more drastic measures are needed. Therefore, ULRP got the right direction to focus on reducing agriculture measures and to provide new water sources for the lake (inter-basin transfer and wastewater). However, proposed new water sources for the lake, in particular inter-basin water transfer, have potentially negative impacts on the basin and environmental impacts on the basin from which water is transferred which might lead to potential future conflicts (Chapter 5). Furthermore, providing additional water, particularly in wet years, can encourage irrigation expansion. Therefore, these measures can be a part of adaptive water management of the basin. It means that the plan should be updated in each stage regarding the climate change trend and water availability. In Chapter 4 of this thesis, I quantified potential agricultural and new water source measures proposed by ULRP.

6.2.3. Quantitative assessment of Urmia Lake Restoration Program (Q3)

The water-saving framework application for Urmia Lake basin revealed that under a limited socioeconomic and climate change (RCP 2.6) scenario the policy could reach the water saving target. Having said that, this is under the assumption that ULRP is fully implemented which is unlikely. Therefore, it is very well possible that ULRP does not achieve its stated goal, despite the huge investment and the social and economic impacts of the proposed interventions. While reduction of irrigation water use can play the main role to restore the lake (Chapter 2 and 3), the framework revealed that ULRP agricultural measures may not have the expected impact on increasing inflow.

In addition, ULRP proposed interventions are ignoring the impact of future climate and socioeconomic changes. However, the results of this study show that the performance of the proposed interventions is more sensitive to changes in climate, rather than to socioeconomic changes.

The results showed that additional water sources, namely inter-basin transfer and treated wastewater, are the most effective measures for increasing inflow. However, these interventions are also accompanied by side-effects, associated with environmentally unsustainable outcomes. In the Chapter 5 of this thesis, the effectiveness of all ULRP measures including agricultural measures and inter-basin water transfer were analyzed.

6.2.4. The qualitative assessment of Urmia Lake Restoration Program (Q4)

In general, the qualitative assessment showed that demand side measures such as crop pattern changes and irrigation efficiency improvements can be more effective and feasible, as opposed to supply-side measures such as inter-basin transfer.

While reducing irrigation water use has to be a high priority to restore Urmia Lake (Chapter 2 and 3), agricultural measures would probably not have a noticeable impact on the lake inflow. The reason is that increased irrigation efficiency would also lead to decreased return flows, and the preserved supply would merely compensate for the present water shortage experienced by the agricultural sector in the basin (Chapter 4). Along with these quantitative reasons, there are more qualitative reasons that made ULRP agriculture measures less effective. The first reason is that increases in water availability (due to higher irrigation efficiency) most probably encourages the farmers to increase the irrigated land. Another reason is that the success of ULRP agricultural measures is highly dependent on controlling water withdrawals, which currently remains a serious challenge in the basin. This reflects the existing issues with water use regulation and implementation in the area, which can be a hidden barrier to the success of ULRP agricultural measures. The third reason is the large amounts of loans and/or direct purchasing of water rights which make it easy for fraud and corruption to happen.

Decreasing irrigation water use can help to increase inflow; however, it would not be enough to provide 3.7 $\times 10^9$ $m^3 yr^{-1}$ EFR (Chapter 3). In addition, to restore the lake a considerable amount of water should be transferred to the lake to make up for the lost water volume. Some studies suggested that at least $19\times10^9 m^3$ of water would be needed to rescue the lake (ULRP, 2015b). This amount of water is much more than the available water inside the basin (Chapter 2). Therefore, two new water sources have been considered by ULRP, which include the Zaab River and urban and industrial wastewater. While ULRP agricultural measures may not have a considerable impact on inflow, the other mentioned measures can increase inflow by up to 57% (Chapter 4). Therefore, providing a new water source for the lake seems unavoidable in order to restore the lake. However, this category of measures, “Water Supply from new water resources”, ranked the least feasible among other categories, as it affects the equity, ecological integrity and economic efficiency; in addition, they can encourage an increase water use (Chapter 5). This calls for more innovative ways of using a new water supply in order to minimize the side effects. As the inter-basin transfer project has already under progress, one solution is that inter-basin water is used in dry years and only for the lake. Over the last decades, there has been a visible inter-annual variation in rainfall, which is a cycle of ~five wet years with above average rainfall followed by ~five dry years with relatively low precipitation (Chapter 2), which can be used for the initial adaptive planning. This can be combined with the *“... adjusting reservoirs operational rules”* measure as indicated in Chapter 3, to provide more water supply in dry years.

To implement Urmia Lake rescue program successfully contributions of all stakeholder, particularly local residents, are essential. Therefore, it is expected from all stakeholders, especially from the agricultural sector, not only to participate effectively in the implementation of programs but also to cooperate on decreasing the volume of agricultural water consumption and supplying the lake-required water (Chapter 5). This shows the role of public awareness in this matter of stakeholders. The public awareness should not only focus on the appropriate way to use irrigation water but also should focus on potentially decreasing water availabilities due to climate change (Chapter 2). To do so, the URLP measure to “*Establish Watershed Management Council with the participation of all interested parties and stakeholders*” can help to prompt a dialogue between scientists and different stakeholders (Chapter 5).

6.3. Toward sustainable approach to preserve Urmia Lake

The results of this thesis showed that current shrinkage and degradation of Lake Urmia is caused by overconsumption of water resources, mainly for irrigated agriculture, in a context where climate change puts more pressure on water availability (Chapter 2). The climate change impact is likely to continue in both the lowest and highest scenarios, so that even drastic changes in the basin water resources management plan might not be enough to provide the required environmental flow to restore and preserve the lake, in particular, under the rapid climate change scenario (Chapter 2). The quantitative assessment also showed that **water supply-oriented** measures would not only increase inflow to the lake the most but also the success of the restoration plan depends on them (Chapter 3). At the same time, these measures are seen as the least feasible measures (Chapter 4). On the other hand, **demand-oriented** measures were the most recommended measures by experts (Chapter 5), but may not have a considerable quantitative impact on inflow (Chapter 4). Also, the field visits to the basin showed that these measures have serious implementation challenges (Chapter 5).

Therefore, the sustainable approach to preserve Urmia Lake should incorporate both demand management (considering socioeconomic complexity) and flexible supply management strategies (to deal with climate variability and change uncertainty) in a participatory approach. Demand management refers to modify irrigation water use by changing crops to high-value crops, reduce water requirements, and increase irrigation efficiency in areas that have high none-beneficial depletion (Chapter 3). However, the qualitative assessment showed that reducing irrigation water use is a serious challenge (Chapter 5), and might not even be enough in the case of success (Chapter 3 and 4). Therefore, to prevent further environmental degradation, this study suggests reducing irrigated land which means reducing the agricultural sector. This will guarantee irrigation water use reduction despite social and climate uncertainties. However, it should be applied in a phase-based manner and after providing alternative livelihoods for the farmers, which are less dependent on water resources. To deal with implementation barriers it will be needed to support the operational mechanisms. Therefore, it is necessary to clarify who will make decisions, who will implement them and who will be responsible. In addition, the local people should be encouraged to involve communities to help save water and save the lake (UNDP, 2014).

The flexible water-supply management should consider climate seasonal and interannual variabilities. Therefore, water-supply oriented measures should only be applied during climatic dry periods to prevent irreversible impacts on the Lake. If water-supply oriented measures are applied the whole time, the surplus water in wet periods may cause undesirable water resources developments. The planning can be defined by considering both the basin seasonal and inter-annual climate variabilities. Seasonal climate variabilities can be addressed by improving the real-time operation of dams, e.g release part of the spring run-off stored water behind the dams in the none-irrigation season (Chapter 3) and wastewater use over dry months. The inter-annual climate patterns can be addressed by inter-basin transfer (e.g in three years dry period).

To be prepared for the future, scenarios with reduced inflow into Urmia Lake, either due to climate change or water resources management, also need to be considered. This requires adaptive and flexible management strategies and governance arrangements which should be rigorously evaluated. In this way the measures are able to deal with considerable amounts of variabilities in the current system and with future changes in climate and socioeconomic conditions. In the case of rapid climate and socioeconomic scenarios, partial recovery by reducing the size of the Lake should also be considered. This can partially preserve the ecosystem until more water becomes available (UNDP, 2014).

6.4. Scientific contribution to water resources management

Climate change is likely to decrease water availability in (semi)-arid areas (Vörösmarty et al., 2010). At the same time, water demand, especially for irrigation, is often increasing in these areas (Haddeland et al., 2014). Therefore, any type of assessment aiming to inform adaptation or mitigation planning needs to undertake both climate and agricultural water resources development (Harrison et al., 2016). However, there is very little information available on integrated climate change impacts, particularly on the regional scale (IPCC, 2014). This is a major barrier to developing successful conservation strategies (Harrison et al., 2016). Therefore, this study regionalized and applied VIC irrigation and reservoirs modulus to do an integrated assessment of the combined and individual impact of climate variabilities and change, and agricultural water resources management on a regional scale (Chapter 2 and 3). This study presented a more robust approach from the previous studies, which assessed only climate variabilities data like annual precipitation (AghaKouchak et al, 2015 Arkian et al., 2016, Fathian et al., 2014) by addressing indirect climate impacts. By applying the integrated approach, this study showed that the water resources plans are not robust enough for the strong climate changes. In other words, only if future climate change is limited due to rapid mitigation measures, the reduction of irrigation water uses can help to preserve the lake. This revealed that urgent adaptation (to limit anthropogenic impact) and mitigation (to limit greenhouse-gas concentration) actions are needed jointly to protect vulnerable natural resources.

This thesis introduced a framework to generate a simple and informative overview that can be used to evaluate proposed water-saving interventions (Chapter 4). Although, several national and international organizations introduced different water accounting frameworks to identify, quantify and report water-related information (Karimi et al., 2013, UN, 2003, Hoekstra et al., 2009), none of the frameworks were specifically designed to assess a water-saving intervention, and their results are not suited to adequately inform policy makers on the efficacy of the water-saving interventions. The innovative aspects of the framework are three-fold. Firstly, it applies integration of cross-sectoral assessments by introducing socioeconomic scenarios to the water-saving intervention assessment along with climate change and agricultural water resources management. Therefore, the framework took into account uncertainties in water availability under climate change, and demand in domestic, industrial and agricultural sectors. In addition, the framework considers the interaction between different sectors under different climate change scenarios. Secondly, the role of the rebound effect can be analyzed systematically by explicitly distinguishing between water withdrawal and water depletion. Thirdly, it discloses any possible shortage or over-exploitation in the basin by an explicit recognition of the total water demand and water withdrawals. Although this effect can play a serious role in the intervention aiming to save water for the environment, to our knowledge it has not been included in previous studies. We therefore included in this study. The framework can also be used to evaluate the impact of water-saving policies on groundwater resources.

This study showed that the quantitative approaches are vital to have a better understanding of the water resource management in any basin (Chapter 4). However, they can only interpret what can be quantified in a credible way (Van Der Sluijs et al., 2005). This study showed that quantitative assessment results can even disagree with qualitative assessment results. For example, while inter-basin transfer ranked the highest effective measure to restore Urmia Lake quantitatively, it got the lowest ranked in a qualitative assessment (vice versa for reducing irrigation water use). Therefore, adaption strategies assessments without taking into account qualitative assessments can lead scientists in a wrong direction. This also implies to develop the middle-road strategies considering both quantitative and qualitative impacts. For example, inter-basin water transfer can be considered only as a short-term solution, while the long-term strategies (like irrigation water use) are under developed.

(Hyper)-saline lakes are important parts of the world's inland aquatic ecosystems with considerable visual, cultural, economic, recreational, scientific, and ecological values (Williams, 2002, Hammer, 1986). However, their global rapidity desiccating trend needs an especial care due to its irreversible negative socio-environmental impacts. Desiccating Lake Poopó in Bolivia (Seiler, 2014), Owens Lake, in California, USA (Costa-Cabral et al., 2013), and Hamun Lake on the Iran-Afghan border (UNDP, 2014) are some examples of this trend. The results of this study confirmed the important role of climate variability and change on (Hyper)-saline lake (Chapter 2). The (hyper)-saline lakes mostly located in (semi)-arid area (Williams, 2002), where a relatively low runoff coefficient cause a high vulnerability to climate variability. On the other hand, (hyper)-saline lake classified as highly vulnerable of ecosystem means that any small changes in their environment can have an irreversible impact on their ecosystem. This study also confirmed the high level of vulnerability of salt lakes to future climate change (Chapter 3). In response, this study suggested to adopt the Environmental Flow Requirements (EFRs) method (Chapter 3) for (hyper)-saline lakes which also take into account the inter-annual variability of their highly vulnerable ecosystem in order to give a higher protection. In addition, most (hyper)-saline lakes are located in endorheic basins. The results of this study showed the important role of rebound effect in such a basin (Chapter4), due to an important role of return flow. In an endorheic basin, the return flow is not a "real lost", as it will join the environment eventually. This situation differs from the basins which drain into sea or ocean because the return flow may exit for the basin and not be available for further use. Therefore, this study suggested to focus on saving the (hyper)-saline through decreasing in the basin water depletion rather than increasing efficiency.

Overall, this study included a cross-sectoral approach to assess the challenge of preserving an endangered natural environment under different climate change, agricultural water resources development and socioeconomic scenarios. Impact assessments that do not account for interactions between influential sectors have the potential to misrepresent impacts as one factor can have indirect effects in others. For example, the impact of changing interannual climate variability, which caused longer dry periods in Urmia basin (Arkian et al., 2016, Harrison et al., 2016) can encourage increased water extractions. The study also created an even more complete or holistic picture by combining the scenario-based quantitative assessment with a qualitative assessment. The approach and results presented in this study can not only assist in preserving Urmia lake and the implementation of the restoration program but can also contribute to a cross-sectoral study addressing the interaction between climate change impact, human water use and natural environment, in particular those interested in studying the similar environmental consequences of water scarcity.

6.5. Reflection on methods and direction of future research

This study assessed the challenge of preserving Urmia Lake under climate change, water management developments and socioeconomic scenarios. However, this study focused on Urmia lake annual inflow, in a basin level. Therefore, the results of this study do not present dry and wet seasons distinctions. Therefore, the approach can be further used in finer spatial and temporal resolution. This helps to understand where the particular measures are needed. For example, across the basin, potential evaporation varies strongly. This is likely to be reflected in other parameters such as irrigation efficiency, water depletion or return flow. Therefore, the next step can be to apply the method (both modelling framework and water-saving policy assessment framework) for finer spatial resolutions (e.g subbasin) and finer temporal resolution (e.g seasonal to assess the seasonal variations including dry and wet seasons). However, such an approach depends on data availability.

This thesis used to two values for Urmia Lake Environmental Flow Requirements (EFRs). The first value was EFRs estimated by (Abbaspour and Nazaridoust, 2007) which also has been defined as

Urmia Lake Restoration Program target (ULRP, 2016b). Their study is based on the assumption that 240 (g/l) NaCl is the threshold that *Atemia urmiuana* can tolerate However, Agh (2007) reported the negative impact on survival, growth and reproductive of *Artemia urmania* at salinity levels ranging from 75 to 175g/l in a 23-day long experiment. Higher salt concentration was not tested, but analyses of other species of *Artemia* reported no survival above 230 g/l (Browne and Hoopes, 1990). The second value was EFRs estimated by adapting Variable Monthly Flow (VMF) method, which takes intra-annual variability into account, for hypersaline lakes. However, none of these methods considered the recent volatile geomorphological situation of the lake. Due to the recent reduction in lake volume the salinity of the lake water has increased sharply causing about 8 billion tons of salt to fill up the deeper parts of the lake. A recent investigation by ULRP revealed that the depth of the deepest part of the lake changed from 16m to only 2m over the period 1995-2015. Although the drop in water level was only around 7m, a layer of salt of around 7m as well, has filled up the deeper parts of the lake. The ratio of the area to the volume (m^2/m^3) has thus increased considerably, meaning that for the same volume of water much more evaporation is expected. Therefore, an in-depth study to review the Urmia Lake environmental flow requirement is recommended to take into account the lake recent geomorphological situation.

This study focused mostly on ULRP measures; while assessment of other alternative measures is also recommended. The measures can be taken from other international cases. They can be, but are not limited to, reduction in evaporation from soil, development of more water-efficient dietary patterns, reductions in meat consumption, importing agricultural goods (or ‘virtual water’) into water-stressed regions (Karimi et al., 2013b, Wada et al., 2014, Sun et al., 2015).

Urmia Lake socio-environmental problem belongs to a bigger expanding problem in the whole country. However, Urmia Lake as a highly vulnerable ecosystem has responded to the problem much quicker. Indeed, Iran is experiencing a severe water scarcity, similar to several other countries of the Middle-east. The population growth, politically aspiration to food self-sufficiency, socioeconomic development which is further intensified by the negative impacts of climate change, resulted in several water-related crises in the region. Therefore, a further study can build on the approach and the result of this study to develop an effective policy to deal with water scarcity in Iran and in a broader context in the Middle-east.

This study shows that climate change has a considerable impact on Urmia basin water resources which is likely to continue in the next century. This will put more pressure on Urmia Lake different water use sectors (agriculture, domestic and industrial) as well as natural resources. To deal with this issue, a better understanding of ‘water-energy-food-environmental nexus’ under climate change by taking into account quantitative and qualitative interactions between different water users can be a fundamental step towards sustainable water management in this water-stressed region.

Supplementary Information

Supplementary information 1 (Chapter 5):

The questionnaire forms asking the experts to score the proposed measures to restore Urmia Lake.

Dear colleague, the below table includes the measures proposed to restore Urmia Lake. We appreciate your participation in scoring these measures.

Name (optional):
Background:
Affiliation:

	Measures / Score	Very strong	Strong	medium	waek	very weak
1	Prohibition on any increases in withdrawals from the basin's water resources and prevent new development, especially in the agricultural sector.					
2	Prevent the unauthorized withdrawals of surface water.					
3	Stop all the dam projects in the study and implementation plans (excluding Shahid Madani and Cheraghveis dams) and the irrigation systems and water supply projects of downstream in the Urmia lake catchment, storage and release of water in the Shahid Madani dam exclusively for Lake of Urmia.					
4	Funding and accelerate in water transfer project the transfer water from the Zab river to Uromia lake basin.					
5	Develop and implement a comprehensive program of education, information, public awareness and participation of local communities in order to clarify the implications of the current situation and the importance of restoring the lake of Urmia.					
6	Organize Urmia Lake Basin wells and installation of smart meters and volume contours to withdraw control in order to increase the inflow of rivers into Lake of Urmia.					
7	Transfer catchment refineries wastewater to the Urmia Lake.					
8	Applied the plan for Preventing slew .					
9	Reduction of 40% of surface and ground water rights by purchase, by Ministry of Energy, within two years.					
10	Develop and implement programs to enhance the productivity of the remaining 60% of water in the agricultural sector by the Ministry of Agriculture.					

11	Financing and supply required technologies to enhance the productivity remain water by the government.					
12	Transfer water to the islands and wetlands of bordering the lake of Urmia from Hasanloo dam and reopening the water channels entering the southern wetlands.					
13	Preparation of cadastral land of Urmia Lake Basin.					
14	Implement approved projects by the executive organizations, controlling and monitoring the implementation of the projects by the headquarters of the restoration of Urmia Lake.					
15	Design and install the comprehensive decision support systems (integrated) of Urmia Lake Basin.					
16	Study the effects of Shahid Kalantari causeway road on the ecosystem of Urmia Lake and offer improving solutions.					
17	Evaluate the feasibility and industrial utilization of salt lake Urmia compliance with environmental considerations					
18	Transfer rivers water to water bodies of lake.					
19	Identify the centers of production and stabilization of dusts.					
20	Study and implementation ecological conservation program of National Park of Urmia Lake with priority of its Southern area.					
21	Perform the necessary coordination with the judiciary in order to facilitate and accelerate the implementation of determining the duty of without permit wells law, especially wells affecting surface water.					
22	Identified areas affecting the flow of main rivers leading to Lake Urmia, and strengthening them through the watershed and aquifer management in order to increase the volume of water entering the lake.					
23	Develop action plan for wastewater treatment in standards rate and apply for alternatives usage .					
24	Established the Future research center of Urmia Lake by Environment Protection Organization.					
25	Diagnostics of health, social and environmental aspects of drying the part of Urmia Lake, preparing and implementing programs to prevent and reduce the risk of possible effects.					
26	Provide increased employment and alternative livelihood programs by relevant organization.					
27	Feasibility of using new technologies to revive Urmia Lake.					
28	study the Transfer Water Project from Caspian sea to Urmia lake.					
29	The use of halophytes in arid area of lake.					
30	Planning and action to provide the minimum water requirement calculated reservoir to maintain water balance ecological.					

31	Feasibility of reducing the rate of evaporation from the lake (separation of the very small deep parts of the body of lake in dry years) and evaluation of environmental impacts.					
32	Prepare a comprehensive plan for water resources planning at the basin level					
33	Develop a plan for adaptation to climate.					
34	Deliver the volume of water to farms.					
35	Rational pricing of water for agriculture on the basis of cost.					
36	Establish Watershed Management Council with the participation of all interested parties and stakeholders					
37	Reduce water use in agricultural sector by crop pattern change and increase irrigation efficiency.					

Supplementary Information 2 (Chapter 5):

Table S2-a The average score and Standard Deviation (SD) for the measures proposed to restore Urmia Lake regarding the experts' background, the associated measures for each number can be found in the table 5-1

Measure	**Water Resources Management**		**Agriculture**		**Ecology**		**Economy**		**Social science**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	83.3	11.8	94.2	10.5	50	0	75	0	75	0
2	87.5	19.1	78.8	9	68.8	10.8	87.5	12.5	75	20.4
3	80.6	17.8	88.5	12.5	62.5	12.5	75	0	66.7	11.8
4	86.1	15	71.2	13.3	75	25	75	25	58.3	11.8
5	84.7	12.2	59.6	12.2	81.2	20.7	62.5	12.5	75	0
6	86.1	12.4	65.4	12.2	62.5	21.7	75	0	41.7	11.8
7	83.3	14.4	63.5	18.6	62.5	12.5	75	0	58.3	11.8
8	65.3	14.8	69.2	10.5	75	17.7	75	0	75	0
9	62.5	12.5	76.9	6.7	62.5	12.5	75	0	58.3	11.8
10	62.5	12.5	76.9	6.7	62.5	12.5	75	0	58.3	11.8
11	76.4	10.1	48.1	11.9	68.8	10.8	87.5	12.5	50	0
12	72.2	7.9	61.5	12.5	50	0	50	0	50	0
13	68.1	14	53.8	9	93.8	10.8	50	0	25	0
14	65.3	12.2	63.5	15.9	50	0	37.5	12.5	58.3	11.8
15	58.3	25	65.4	20.9	56.2	10.8	75	0	58.3	11.8
16	61.1	12.4	50	17	68.8	10.8	50	0	91.7	11.8
17	65.3	17	51.9	11.9	56.2	10.8	75	0	58.3	11.8
18	65.3	14.8	44.2	20	75	0	62.5	12.5	58.3	11.8

19	69.4	17.8	48.1	6.7	62.5	12.5	50	0	50	0
20	58.3	11.8	51.9	6.7	56.2	20.7	75	0	75	0
21	44.4	15.7	44.2	14.4	75	0	62.5	12.5	33.3	11.8
22	65.3	12.2	48.1	11.9	37.5	12.5	37.5	12.5	50	0
23	52.8	11.5	46.2	13.3	81.2	10.8	50	0	50	0
24	50	14.4	51.9	11.9	43.8	10.8	50	0	91.7	11.8
25	51.4	15.5	50	0	75	0	50	0	50	0
26	44.4	15.7	55.8	20	56.2	10.8	62.5	12.5	58.3	11.8
27	51.4	43.7	59.6	47.6	25	30.6	0	0	66.7	47.1
28	66.7	38.2	38.5	38.7	43.8	10.8	25	0	25	0
29	58.3	26.4	40.4	18.4	43.8	10.8	50	0	50	0
30	45.8	19.1	57.7	18	25	17.7	37.5	12.5	41.7	11.8
31	45.8	17.2	26.9	18.2	68.8	10.8	62.5	12.5	75	0
32	55.6	15.7	36.5	15.9	62.5	12.5	0	0	0	0
33	31.9	20.1	44.2	20	50	0	37.5	12.5	75	0
34	34.7	17	34.6	15.6	50	0	62.5	12.5	41.7	11.8
35	52.8	18.4	28.8	9	25	0	25	0	16.7	11.8
36	48.6	29.4	25	25.9	18.8	10.8	0	0	16.7	11.8
37	33.3	22	15.4	20.9	18.8	10.8	0	0	16.7	11.8

Table S2-b The average score and Standard Deviation (SD) for the measures proposed to restore Urmia Lake regarding the experts' affiliation, the associated measures for each number can be found in the table 5-1

Measure	**Policy Makers**		**Scientists**	
	Mean	SD	Mean	SD
1	83.8	11.9	81.5	18.4
2	89.7	15	76.1	15.6
3	82.4	18.7	78.3	15.3
4	79.4	15.4	76.1	20.2
5	79.4	17.6	70.7	15.9
6	77.9	16.9	69.6	19.4
7	77.9	16.9	68.5	18.4
8	66.2	11.9	70.7	14.1
9	63.2	12.5	70.7	12
10	63.2	12.5	70.7	12

11	69.1	20.2	62	14.5
12	70.6	9.5	58.7	11.9
13	66.2	14.7	58.7	21.6
14	66.2	11.9	57.6	15.5
15	54.4	21.4	66.3	20.3
16	58.8	17	60.9	17.8
17	61.8	19.4	58.7	11.9
18	69.1	13.6	51.1	18.8
19	70.6	15.4	51.1	11.6
20	55.9	10.6	59.8	14.3
21	45.6	15.4	48.9	18.8
22	63.2	12.5	47.8	14.6
23	51.5	10.4	54.3	17.5
24	48.5	10.4	56.5	19.8
25	47.1	11.8	57.6	11.5
26	41.2	17	58.7	14
27	60.3	42.1	42.4	46.9
28	89.7	12.3	20.7	17.5
29	58.8	27	43.5	15.1
30	58.8	17	38	17.9
31	47.1	18.9	43.5	24.7
32	51.5	21.8	37	23.2
33	35.3	19.3	45.7	21.7
34	33.8	14.7	41.3	17.5
35	52.9	18.9	27.2	10.2
36	63.2	15.1	10.9	12.4
37	42.6	16.6	8.7	11.9

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Summary

To supply food and energy for a growing population, humans developed reservoirs and extract water for irrigation. Furthermore, climate change has a significant impact on the natural hydrological cycle and amplifies water scarcity in (semi)-arid regions. Consequently, water demand has approached or is approaching water availability in many basins. This leaves limited volumes of water for the natural environment. Therefore, managing water for a growing population without having devastating effects on natural resources is becoming a serious challenge. These trends are likely to increase by future climate change. Therefore, to prevent further degradation and to promote resilience to drought, water policies have been changing to manage environmental flow requirement. However, so many of these policies not only failed to reach their goals, but also weaken basin resilience through loss of flexibility and redundancy. These complex challenges call for an urgent and comprehensive assessment, in particular for highly endangered ecosystems, on how climate and anthropogenic changes will affect required environmental flows and on how water-saving policies can effectively deal with those future changes. This thesis, therefore, assesses climate and anthropogenic changes on environmental flow of Urmia Lake, a highly degraded hyper-saline lake in north-western Iran. In addition, the thesis assesses the effectiveness of policies aiming to restore and preserve the Lake.

Urmia Lake, in north-western Iran, is an important internationally recognized natural area designated as a RAMSAR site and UNESCO Biosphere Reserve. It is a home to many species along with a unique brine shrimp species. Urmia Basin supports a variety of agricultural production systems and activities as well as livestock. The basin is located in a politically tensed region bordering both Iraq and Turkey. It is a linguistically and culturally diverse area dominated by two ethnic groups, Azeri Turks and Kurdish. Over the last 20 years, the surface area of Urmia Lake has declined by 80%. As a result, the salinity of the lake has sharply increased which is disturbing the ecosystems, local agriculture and livelihoods, regional health, as well as tourism. Several studies have warned that the future of Urmia Lake could become similar to the Aral Sea, which has dried up over the past several decades and severely affected the surrounding people with windblown salt storms. The population around Urmia Lake, however, is much denser compared to the Aral Sea and many more people are at risk. Local reports have indicated that thousands of people around the lake have already abandoned the area. It has been estimated that people living within 500 km of the Lake location, are at risk, which could amplify economic, political and ethnic tensions in this already volatile region.

In the first step, this thesis assessed the main reasons for the decreased inflow using the Variable Infiltration Capacity (VIC) hydrological model, including reservoirs and irrigation modules, over the period 1960-2010 **(Chapter 2)**. The model results showed that decreases in inflow generally follow observed decreases in precipitation, though the variability in inflow is more pronounced than the variability in precipitation. The results also suggested that water use for irrigation has increased pressure on the basin’s water availability and has caused flows to decrease by as much as 40% during dry years. On the other hand, the presence of reservoirs positively contributed to water availability during relatively dry years and did not significantly reduce lake inflow. By irrigation expansion in the basin, reservoirs have, however indirectly, contributed to inflow reduction. The results showed that annual inflow to Urmia Lake has dropped by 48% over the study period. About three-fifths of this change was caused by climate change and about two-fifths was caused by water resources development. Therefore, climate change was the main contributor to this inflow reduction.

In the second step, this thesis assessed Urmia lake inflow under future climate change and irrigation scenarios **(Chapter 3)**. By adapting a method of environmental flow requirements (EFRs) for hypersaline lakes, the study estimated annually 3.7×10^9 m^3 water is needed to preserve Urmia Lake. Then, the Variable Infiltration Capacity (VIC) hydrological model was forced with bias-corrected climate model outputs for both the lowest (RCP2.6) and highest (RCP8.5) greenhouse-gas concentration scenarios to estimate future water availability and impacts of water management strategies. Results showed a 10% decline in future water availability in the basin under RCP2.6 and 27% under RCP8.5. Our results showed that if future climate change is highly limited (RCP2.6) inflow can be just enough to meet the EFRs by implementing the reduction irrigation plan. However, under more rapid climate change scenario (RCP8.5) reducing irrigation water use will not be enough to save the lake and more drastic measures are needed. The results showed that future water management plans are not robust under climate change in this region.

In response to deteriorating Urmia Lake conditions, Iranian government established the ten-year "Urmia Lake Restoration Program (ULRP)" which includes six categories of measures. The first category is *control and reduction of water depletion in the agricultural sector*. This category suggests the purchase of 40% of farmers' water rights by the government to the lake, along with increasing efficiency and productivity in the agricultural sector. The second category is *control and reduction of withdrawal from surface and groundwater resources in the Basin* by preventing unauthorized water withdrawals and passing supporting legislation. The third category is *initiatives on protection and mitigation of negative impacts*. These will study about health problems caused by the desiccation of the lake and also about alternative employment opportunities. The forth category is s*tudies and software measures*, which will promote public awareness and capacity building, and developing a decision-support system. The fifth category is *facilitation and increase of the water volume entering the lake through structural measures.* This category promotes the building of a network of waterways to bring available river water into the lake. The sixth category is *water supply from additional water resources.* The additional water resources are inter-basin water transfer from Zaab basin and the basin urban and industrial wastewater.

The third step assessed the quantitative impacts of official Urmia Lake Restoration Plan (ULRP) under future climate change and socioeconomic scenarios on the lake's inflow **(Chapter 4)**. To address this objective this step focused on those measures that directly affect Urmia Lake inflow. This step introduced a constructive policy-assessment framework that estimates five components: i) total water demand under socioeconomic scenarios; ii) water supply under climate change scenarios; iii) water withdrawal for different sectors; iv) water depletion; and v) environmental flow. Results suggested that although the ULRP helps to increase inflow by up to 57%, it is unlikely to reach its target. The analysis showed three main reasons for this potentially poor performance. These were: i) decreasing return flows due to increasing irrigation efficiency, meaning that the expected increase in lake inflow volume is smaller than the volume saved by increasing irrigation efficiency; ii) increased depletion, because the fact that agricultural water demand is currently higher than available water for agriculture has been overlooked and, as a result, increased water use efficiency may result in increased water depletion; iii) the potential impact of climate change, which could decrease future water availability by 3–15%, has been ignored. The analysis suggested that to reach the intervention target, measures need to focus on reducing water demand and water depletion rather than on reducing water withdrawals.

While the quantitative assessment of the plan showed that ULRP could reach its target only under a limited climate change scenario, there are additional barriers and challenges that may cause the failure of the plan or its implementation costs to become excessive. In the fourth step of this study **(Chapter 5)**, hence, two types of qualitative data were used: first, the findings from 40 experts who were asked to score the ULRP measures proposed to restore the lake; and second, analyses and discussions based on the in-situ observation of some of the ULRP implementation practices and modalities. The results indicated a number of challenges for the ULRP, including i) the need for proper enforcement of existing water use and development regulations; and ii) the revision of ULRP agricultural measures to control agricultural water demand (such as through crop pattern changes and targeted irrigation-efficiency improvements). The large scale infrastructure interventions, such as inter-basin water transfer, received the lowest support by experts. However, there were considerable disagreements about these measures among experts. In general, (water) demand-side measures such as crop pattern changes and irrigation efficiency improvements seemed more feasible, as opposed to supply-side measures.

This thesis showed that **(Chapter 6)** the sustainable approach to preserve Urmia Lake should incorporate both demand management (considering socioeconomic complexity) and flexible supply management strategies (to deal with uncertainties in climate variability and change) in a participatory approach. To be prepared for the future, also scenarios with reduced inflow into Urmia Lake, either due to climate change or water resources development, need to be considered. This requires adaptive and flexible management strategies and governance arrangements which should be rigorously evaluated. In this way, the measures are able to deal with considerable amounts of variability in the current system and with future changes in climate and socioeconomic conditions.

Overall, this study integrated cross-sectoral approaches to assess the challenge of preserving endangered natural environment under different climate change, water resources development and socioeconomic scenarios. The study also created even a more holistic picture by combining a scenario-based quantitative assessment with a qualitative assessment. The approach and results presented in this study not only can assist in preserving Urmia lake and implementation of the restoration program, but also can contribute to cross-sectoral studies addressing the interaction between climate change impact, human water use and natural environment, in particular in (semi)-arid areas.

Samenvatting

Om een groeiende bevolking te voorzien van voedsel en energie zijn dammen gebouwd en wordt water onttrokken voor irrigatie. Daarnaast heeft klimaatverandering een sterke invloed op de hydrologische cyclus en vergroot het de waterschaarste in semi-aride en aride gebieden. In veel stroomgebieden benadert de watervraag hierdoor de waterbeschikbaarheid. Dit beperkt ook de waterbeschikbaarheid voor de natuurlijke omgeving. Hierdoor wordt duurzaam waterbeheer een steeds moeilijker bereikbaardere opgave. Toekomstige klimaatverandering kan dit nog verder bemoeilijken. Om verdere achteruitgang te voorkomen en de weerbaarheid van de natuur te vergroten is waterbeleid er op gericht geweest om in de natuurlijke waterbehoefte te blijven voorzien. Vaak werden doelen echter niet bereikt, of werd de weerbaarheid van het watersysteem zelfs aangetast. De complexe uitdagingen vragen om een kordate en weloverwogen analyse van natuurlijke en menselijke invloeden op waterschaarste voor zowel mens als natuur, als basis voor een effectief waterbesparend beleid. Deze dissertatie behandelt de invloeden van het klimaat en de mens op de instroom van het Urmiameer, een sterk aangetast hyperzout meer in Noordwest Iran. Daarnaast wordt ook de effectiviteit van het beleid dat zich richt op het herstel en behoud van het Urmiameer geanalyseerd.

Het Urmiameer, gelegen in Noordwest Iran, is een belangrijk internationaal erkend natuurgebied dat officieel geregistreerd staat als RAMSAR locatie en UNESCO Biosphere Reserve. Het ecosysteem ondersteunt veel plant- en diersoorten, waaronder een unieke garnalensoort. Daarnaast vinden in het stroomgebied van het Urmiameer verschillende vormen van akkerbouw en veeteelt plaats. In het gebied, grenzend aan Irak en Turkije, heersen ook politieke spanningen. In dit deel van de cultureel en taalkundig diverse regio zijn de Azeri en de Koerden de dominante bevolkingsgroepen. In de afgelopen twintig jaar is het wateroppervlak van het Urmiameer met tachtig procent afgenomen. Het resulterende hoge zoutgehalte van het meer heeft geleid tot problemen in relatie tot onder meer het ecosysteem, de landbouw de volksgezondheid, de toerismesector. Verschillende studies hebben gewaarschuwd voor een toekomst zoals die van het Aralmeer dat recentelijk compleet opdroogde met ernstige negatieve gevolgen voor de lokale bevolking. Vanwege de relatief hoge bevolkingsdichtheid in het gebied rond het Urmiameer gaat het probleem hier ook relatief veel mensen aan. Lokale berichtgeving duidt op een vertrek van mensen uit het gebied. Gezondheidseffecten kunnen tot wel 500 kilometer vanaf het Urmiameer worden ervaren, met mogelijke economische, etnische en politieke gevolgen bovenop een nu al kwetsbare situatie.

Eest worden in deze dissertatie de belangrijkste oorzaken van een afgenomen instroom van het Urmiameer, in de periode 1960-2010, geëvalueerd (**Hoofdstuk 2**). Hiervoor is het Variable Infiltration Capacity (VIC) hydrologisch simulatiemodel gebruikt, inclusief de *Reservoirs* en *Irrigation* modules. De model resultaten tonen aan dat de afgenomen instroom samenhangen met een teruggelopen neerslaghoeveelheid in het stroomgebied. Echter, de variatie in instroomvolumes is duidelijk sterker dan die van neerslagvolumes. Daarnaast duiden de resultaten erop dat waterverbruik voor irrigatie de druk op de waterbeschikbaarheid in het gebied heeft vergroot en daarmee de toestroom naar het Urmiameer in droge jaren met ongeveer veertig procent heeft verlaagd. De aanwezigheid van dammen in het gebied heeft de waterbeschikbaarheid in droge jaren positief beïnvloedt en de instroom niet direct significant verlaagd. Via de toegenomen irrigatie in het stroomgebied hebben de dammen echter wel degelijk bijgedragen aan de instroomafname. De resultaten laten een afname zien van achtenveertig procent voor jaarlijkse instroom voor de periode 1960-2010. Tweederde van deze afname relateert aan klimaatverandering terwijl éénderde werd veroorzaakt door veranderd

watergebruik. In dit opzicht was de bijdrage van klimaatverandering aan de instroomreductie dus groter dan die van watergebruik.

In een tweede stap, worden in deze dissertatie de effecten van toekomstige ontwikkelingen met betrekking tot klimaat en irrigatie op de instroom van het Urmiameer geëvalueerd (**Hoofdstuk 3**). Door het toepassen van een methode voor environmental flow requirements (EFRs) voor hyperzoute meren werd een instroombehoefte van $3.7 \cdot 10^9$ m^3 water voor het Urmiameer geschat. Om toekomstige waterbeschikbaarheid en de invloed van waterbeheerstrategieën te evalueren werd het VIC model opnieuw gebruikt. Hierbij werd ook gebruik gemaakt van gecorrigeerde klimaatmodeluitkomsten voor twee greenhouse-gas emissie scenario's (RCP2.6 en RCP8.5). De resultaten tonen afnames van tien en zevenentwintig procent aan voor waterbeschikbaarheid voor respectievelijk RCP2.6 en RCP8.5. Onze resultaten laten zien dat beperkte klimaatverandering (RCP2.6) kan leiden tot een situatie waarin net wordt voldaan aan EFRs, wanneer een irrigatiereductie plan geïmplementeerd wordt. Bij snellere klimaatverandering (RCP8.5) zal eenzelfde irrigatiereductie niet leiden tot voldoende instroom voor het Urmiameer. De resultaten tonen dus aan dat de waterbeheersplannen niet robuust zijn met betrekking tot mogelijke klimaatverandering in deze regio.

In reactie op de verslechterde conditie van het Urmiameer startte de Iraanse overheid een tienjarenplan, genaamd "Urmia Lake Restoration Program (ULRP)" waarin gewerkt wordt aan maatregelen binnen zes categorieën. De eerste categorie is het beheersen en beperken van waterverbruik voor de landbouw. De overheid beoogt aankoop van veertig procent van de huidige watergebruiksrechten in combinatie met het verhogen van de efficiëntie en productiviteit in de landbouw. De maatregelen in deze categorie beïnvloeden de instroom naar het Urmiameer direct. Een tweede categorie is het controleren en beperken van wateronttrekking uit oppervlaktewater en grondwater in het gehele stroomgebied. Deze categorie maatregelen dient om uitputting van waterbronnen niet verder te vergroten door te stoppen met projecten en om ongeautoriseerde onttrekkingen te voorkomen via wetgeving en handhaving. Hoewel deze maatregelen de instroom niet direct doen toenemen, voorkomen zij een verdere afname. Een derde categorie richt zich op bescherming tegen, en verzachting van negatieve gevolgen. Deze categorie maatregelen betreft onderzoek naar de volksgezondheid en het creëren van alternatieve werkgelegenheid. Deze maatregelen beogen de lokale bevolking te steunen in hun levensonderhoud. Een vierde categorie maatregelen betreft onderzoek en het ontwikkelen van 'software'. Deze maatregelen dragen bij aan bewustwording en weerbaarheid van de bevolking, onder andere door het ontwikkelen van een beslissingsondersteunend systeem. Een vijfde categorie is het vergroten van instroom naar het Urmiameer door verbeterde infrastructuur. Maatregelen in een zesde categorie betreffen aanvullende waterbronnen zoals water uit nabijgelegen stroomgebieden en het hergebruik van afvalwater. Deze laatste categorie heeft een direct invloed op de instroom naar het Urmiameer.

Een derde methodische stap richt zich op de evaluatie van de gevolgen van het URLP voor de instroom naar het Urmiameer, uitgaande van toekomstige veranderingen op het gebied van klimaat en socio-economische factoren (Hoofdstuk 4). Hiervoor zijn alleen maatregelen meegenomen die direct van invloed zijn op de instroom. In dit hoofdstuk word een beleidsanalyseraamwerk beschreven dat richting geeft aan het schatten van vijf essentiële componenten: i) totale watervraag voor een gegeven socio-economisch scenario; ii) wateraanbod gegeven een klimaatscenario; iii) wateronttrekking door verschillende sectoren; iv) waterverbruik; en v) waterbeschikbaarheid voor de natuur. Ondanks een instroomtoename met zevenenvijftig procent, wijzen de resultaten erop dat het onwaarschijnlijk is dat de ULRP doelen worden bereikt. Hiervoor worden drie redenen gegeven: i) afnemende terugstroming door een toenemende irrigatie-efficiëntie; ii) toenemend consumptief watergebruik door toegenomen beschikbaarheid op lokaal niveau; en iii) verminderd aanbod door klimaatverandering. De onderzoeksuitkomsten suggereren dat voor het behalen van de doelen van ULRP, maatregelen nodig zijn die zich richten op watervraag en waterverbruik in plaats van op wateronttrekkingen.

Hoewel kwantitatieve analyse laat zien dat ULRP doelen kunnen worden bereikt als sprake is van beperkte klimaatverandering (RCP2.6), zijn er daarnaast ook nog andere obstakels en uitdagingen die het welslagen kunnen belemmeren, zoals hoge kosten en praktische bezwaren. In een vierde methodische stap zijn daarom twee typen kwalitatieve data bestudeerd (**Hoofdstuk 5**): i) de beoordelingen van veertig experts ten aanzien van de in het kader van het ULRP voorgestelde maatregelen en ii) in-situ observaties en registraties van aan het ULRP gerelateerde activiteiten en discussies tussen betrokken actoren. De resultaten wezen op een aantal uitdagingen voor het ULRP, waaronder i) adequate handhaving van bestaande regels ten aanzien van watergebruik en gerelateerde activiteiten; en ii) effectieve waterbesparende maatregelen binnen de landbouwsector (zoals veranderingen ten aanzien van gewaskeuze en irrigatie-efficiëntie). Grootschalige infrastructurele investeringen, zoals watertransfer van buiten het stroomgebied naar het Urmiameer, kreeg de laagste beoordeling van experts. Hierover was echter slechts beperkte overeenstemming tussen de verschillende experts. Over het algemeen was kregen demand-management maatregelen meer steun dan supply-management maatregelen.

Deze dissertatie heeft aangetoond dat voor een duurzaam beheer van het Urmiameer zowel demand-management als supply-management maatregelen nodig zijn en rekening wordt gehouden met socio-economische complexiteit door een inclusieve aanpak (**Hoofdstuk 6**). Om voorbereid te zijn op de toekomst dient rekening te worden gehouden met een structureel lagere instroom. Dit vereist een adaptief en flexibel beheer en bestuur dat nauwlettend moet worden geëvalueerd. Op deze manier kunnen maatregelen worden ingezet met inachtneming van de huidige variabiliteit en toekomstige veranderingen ten aanzien van het klimaat en socio-economische ontwikkelingen.

In deze studie zijn verschillende methoden geïntegreerd voor de bestudering van de mogelijkheden om een bedreigde natuurlijke omgeving te beschermen, waarbij rekening houdend met verschillende scenario’s voor klimaatverandering, socio-economische ontwikkelingen en investeringen in de watersector. Door het combineren van een scenario-gebaseerde kwantitatieve benadering met een kwalitatieve benadering heeft deze studie bijgedragen aan een vollediger beeld van zowel de actuele situatie als mogelijke toekomstige situaties. Deze aanpak en de daarmee bereikte resultaten kunnen zowel bijdragen aan het beschermen van het Urmiameer en de implementatie van het ULRP als aan interdisciplinaire studies naar de interacties tussen klimaat, watergebruik en de natuurlijke omgeving.

خلاصه

برای تامین غذا و انرژیِ جمعیتی در حال رشد، انسان‌ها سدها و مخازن آب را توسعه دادند و برای کشاورزی آب استخراج کردند. از سوی دیگر تغییرات آب‌وهوا و اقلیم بر چرخه‌ی طبیعی هیدرولوژیک تاثیری شگرف دارد و کمبود آب را در مناطق (نیمه)خشک تشدید می‌کند. در نتیجه نیاز به آب در بسیاری از حوضه‌ها به مرز آب قابل دسترس نزدیک شده یا در حال نزدیک شدن است. این امر حجم آب محدودی برای زیست‌محیط طبیعی باقی می‌گذارد. از این رو مدیریت آب برای این جمعیت رو به رشد، بدون تاثیرات مخرب بر روی منابع طبیعی در حال تبدیل به چالشی جدی است. این روندها احتمالاً با تغییرات آتی اقلیم نیز افزایش خواهند یافت. به همین دلیل در راستای جلوگیری از نابودی بیشتر منابع طبیعی و افزایش ظرفیت مقابله با خشکسالی، سیاست‌های آب در جهت مدیریت تامین جریان زیست‌محیطی در حال تغییر بوده است. هرچند بسیاری از این سیاست‌ها نه‌تنها از رسیدن به اهداف خود بازمانده‌اند، بلکه انعطاف‌پذیری حوضه را به خشکسالی نیز تضعیف کرده‌اند. این چالش‌های پیچیده دعوتی هستند به یک ارزیابی ضروری و مفصل - به‌ویژه برای اکوسیستم‌هایی که به‌شدت در معرض خطر قرار دارند – که چگونه تغییرات آنتروپوژنیک و اقلیمی، جریان‌های زیست‌محیطی مورد نیاز را تحت تاثیر قرار خواهند داد و چگونه سیاست‌های ذخیره‌ی آب قادرند به صورتی موثر به این تغییرات بپردازند. در همین راستا رساله‌ی پیش رو به برآورد تغییرات تغییرات آنتروپوژنیک و اقلیمی موثر بر کاهش جریان زیست‌محیطی مورد نیاز دریاچه‌ی ارومیه – دریاچه‌ی نمک فوق اشباع (hyper-saline) واقع در شمال غربی ایران – می‌پردازد. علاوه بر این، کارایی سیاست‌هایی را که در جهت حفظ و احیای دریاچه بوده‌اند، ارزیابی می‌کند.

دریاچه‌ی ارومیه در شمال غربی ایران، اکوسیستمی واجد اهمیت بین‌المللی است که در لیست کنوانسیون **رامسر** و در مناطق طبیعی تحت حفاظت **یونسکو** قرار گرفته است. این دریاچه زیستگاه گونه‌های بسیار و از جمله گونه‌ای یکتا از میگوی آب شور است. حوضه‌ی ارومیه دارای تنوعی از سیستم‌ها و فعالیت‌های تولیدی کشاورزی و دامپروری بوده است. این حوضه در منطقه‌ی سیاسی تنش‌مندی هم‌مرز با عراق و ترکیه قرار دارد. منطقه‌ای است به لحاظ زبان‌شناختی و فرهنگی متنوع که دو گروه قومی ترک‌های آذری‌زبان و کردها در آن غالب هستند. مساحت دریاچه‌ی ارومیه در خلال۳۰ سال گذشته تا ۸۰٪ کاهش داشته است. در نتیجه شوری دریاچه به‌شدت بالا رفته، که در اکوسیستم‌ها، کشاورزی محلی، معیشت، سلامت منطقه و همچنین توریسم اخلال ایجاد کرده است. پژوهش‌های مختلف هشدار داده‌اند که آینده‌ی دریاچه‌ی ارومیه می‌تواند مشابه دریاچه‌ی آرال باشد که در طول چند دهه‌ی گذشته خشک شد و مردم مناطق مجاور را با توفان‌های شن و نمک شدیداً تحت تاثیر قرار داد. هرچند جمعیت پیرامون دریاچه‌ی ارومیه در مقایسه با دریاچه‌ی آرال بسیار فشرده‌تر است و جمعیت بیشتری در معرض خطر قرار دارند. گزارش‌های محلی حاکی از آن‌اند که صدها نفر از مردم اطراف دریاچه تا کنون منطقه را ترک کرده‌اند. تخمین زده می‌شود جمعیتی که تا شعاع ۵۰۰ کیلومتری دریاچه زندگی می‌کنند، در معرض خطر باشند؛ موضوعی که می‌تواند به تنش‌های اقتصادی، سیاسی و قومی در این منطقه‌ی بی‌ثبات دامن بزند.

در نخستین گام، این رساله دلایل اصلی کاهش جریان ورودی را با استفاده از مدل هیدرولوژیک ظرفیت نفوذ متغیر (VIC) شامل مدول‌های مخازن و آبیاری را طی سال‌های ۱۹۶۰ تا ۲۰۱۰ ارزیابی کرد **(فصل دوم)**. نتایج این مدل نشان دادند که کاهش بارندگی و کاهش جریان ورودی الگوهای مشابهی را دنبال می‌کنند. گرچه تغییرات جریان ورودی شدیدتر از تغییرات بارندگی است. نتایج همچنین نشان دادند که آبیاری بر روی آب قابل دسترس حوضه فشار بیشتری اعمال کرده، باعث کاهش جریان تا مرز ۴۰٪ در طول این سال‌ها شده‌اند. از سوی دیگر وجود مخازن طی سال‌های نسبتاً خشک به تامین آب کمک کردند و همزمان باعث کاهش قابل ملاحظه‌ای در جریان ورودی دریاچه نیز نشدند. هرچند با شتاب‌بخشی به توسعه‌ی آبیاری در حوضه، مخازن نیز در کاهش جریان ورودی به شکل غیرمستقیم مشارکت داشته‌اند. نتایج نشان دادند که جریان ورودی سالانه به دریاچه‌ی ارومیه تا ۴۸٪ در مقطع زمانی مورد پژوهش تنزل داشته است. حدود سه پنجم این تغییر توسط تغییرات آب‌وهوایی و اقلیم به وجود آمده و حدود دو پنجم آن توسط توسعه‌ی منابع آبی. بنابراین تغییرات آب‌وهوا عامل اصليِ کاهش جریان ورودی بودند.

در گام دوم، رساله به بررسی جریان ورودی دریاچه‌ی ارومیه با توجه به تغییرات آتی اقلیم و سناریوهای آبیاری می‌پردازد **(فصل سوم)**. با تطبیق یک روشِ محاسبه‌ی نیاز جریان زیست‌محیطی (EFRs) برای دریاچه‌های نمک فوق‌اشباع، پژوهش پیش رو تخمین می‌زند که سالانه به ۷٫۳ میلیارد مترمکعب آب برای حفظ دریاچه‌ی ارومیه نیاز است. سپس خروجی‌های خطازدایی‌شده‌ی مدلهای اقلیم برای پایین‌ترین (RCP2.6) و بالاترین (RCP8.5) سناریوهای غلظت گازهای گلخانه‌ای در مدل هیدرولوژیک VIC قرار گرفتند تا دسترسی آتی به آب و اثرات استراتژی‌های مدیریت آب بررسی شود. نتایج نشان دادند که آب قابل دسترس در حوضه، تحت RCP2.6، به میزان ۱۰درصد و تحت RCP8.5، به میزان ۲۷ درصد کاهش پیدا می‌کنند. همچنین در شرایط تغییرات اقلیمی بسیار تحت کنترل (RCP2.6) و اعمال برنامه‌ی کاهش آبیاری، جریان ورودی می‌تواند نیاز جریان زیست‌محیطی دریاچه را تامین کند. اما تحت سناریوی تغییرات اقلیمی سریع‌تر (RCP8.5)، کاهش آب مورد استفاده در آبیاری برای نجات دریاچه کافی نخواهد بود و اقدامات شدیدتری مورد نیاز است. نتایج حاکی از آن‌اند که موفقیت برنامه‌های آینده‌ی مدیریت آب به تغییر اقلیم وابسته هستند.

بدتر شدن شرایط دریاچه‌ی ارومیه منجر به راه‌اندازی «برنامه‌ی احیای دریاچه‌ی ارومیه» (ULRP) توسط دولت ایران شد. ULRP به‌عنوان برنامه‌ای ده‌ساله تصویب شد که شش دسته از راهکارها را در بر می‌گیرد. دسته‌ی اول «کنترل و کاهش مصرف آب در بخش کشاورزی» است. این دسته پیشنهاد می‌دهد که۴۰٪ از حق‌آبه‌ی کشاورزان برای دریاچه تخصیص یابد، به‌همراهِ افزایش راندمان و بارآوری در بخش‌های کشاورزی. دسته‌ی دوم شامل «کنترل و کاهش برداشت آب سطحی و منابع آب زیرزمینی در حوضه» است. این به معنای جلوگیری از افزایش هرگونه برداشت آب غیرمجاز از راه توقف پروژه‌های در حال ساخت و تقویت قوانین حمایتگرانه است. دسته‌ی سوم شامل «اقدامات حفاظتی و کاهش اثرات منفی» است. این دسته بیشتر بر روی پژوهش و مطالعه در باب منشا آن گروه از مشکلات سلامتی تمرکز دارد که در ارتباط با خشکیدن دریاچه و همچنین ایجاد موقعیت‌های بدیل شغلی هستند. گرچه این دسته از راهکارها بر روی جریان ورودی دریاچه تاثیر مستقیمی نخواهد داشت، بر روی موفقیت دیگر راهکارها از طریق بهبود وضع معیشتی مردم اثر مثبت خواهد گذاشت. ردیف چهارم «مطالعات و اقدامات

نرم‌افزاری» است. تمرکز آن بر روی افزایش آگاهی عمومی و افزایش ساخت ظرفیت و علاوه بر آن ایجاد یک سیستم پشتیبانی برای تصمیم‌گیری است. این دسته در موفقیت بقیه‌ی اقدامات نقش بازی خواهد کرد. پنجمین دسته «تسهیل و افزایش حجم آب ورودی به دریاچه از طریق اقدامات فیزیکی و سازه‌ای» است. هدف این دسته از راهکارها افزایش میزان آبی است که از رودخانه به دریاچه می‌رسد، از طریق باز کردن و لایروبی مسیر جریان‌های آبی. دسته‌ی ششم «تامین آب از منابع آب جدید» است. منابع آب جدید انتقال آب بیناحوضه‌ای از حوضه‌ی آبریز زاب و فاضلاب صنعتی و شهری است.

در همین راستا گام سوم به بررسی اثرات برنامه‌ی رسمی احیای دریاچه‌ی ارومیه (ULRP) بر روی جریان ورودی دریاچه تحت سناریوهای اقلیمی و اقتصادی-اجتماعی پرداخته است (فصل چهارم). برای رسیدن به این هدف، گام سوم بر روی آن راهکارهایی متمرکز شد که مستقیماً جریان ورودی دریاچه‌ی ارومیه را تحت تاثیر قرار می‌دهند. پژوهش حاضر چارچوبی عملی برای تخمین «ذخیره‌ی آب واقعی» معرفی کرد. این چارچوب پیشنهاد می‌داد که پنج عامل موثر را مورد سنجش و برآورد قرار دهیم: ۱) تقاضای آب تحت سناریوهای اقتصادی-اجتماعی، ۲) آب قابل دسترس تحت سناریوهای تغییر اقلیم، ۳) برداشت آب از بخش‌های مختلف ۴) آب مصرف‌شده، ۵) جریان زیست‌محیطی. نتایج حکایت از آن داشتند که گرچه ULRP به افزایش جریان ورودی کمک می‌کند، رسیدن کامل به هدف نامحتمل است. این تحلیل سه دلیل اصلی را برای عملکرد ضعیف پیش‌بینی شده پیشنهاد می‌دهد. دلیل نخست اثر عکس‌العملی است: این که با افزایش راندمان کشاورزی، جریان‌های بازگشتی کاهش پیدا می‌کنند. دلیل دوم نادیده گرفتن این واقعیت است که نیاز به آب هم‌اکنون نیز بیش از آب موجود در حوضه است. از این رو افزایش راندمان مصرف آب ضرورتاً به افزایش جریان‌های ورودی دریاچه منتهی نمی‌شود، چرا که آب صرفه‌جویی‌شده ممکن است صرف پر کردن شکاف تقاضای موجود شود. دلیل سوم در نظر نگرفتن اثر بالقوه‌ی تغییر اقلیم است.

در حالی که ارزیابی‌های کمّی نشان دادند که ULRP تنها تحت سناریوی تغییرات اقلیمی محدود می‌تواند به‌طور کامل به هدف‌اش برسد، موانع و چالش‌های دیگری نیز هستند که ممکن است باعث شکست برنامه یا هزینه‌ی هنگفت حین اجرای آن شوند. از این رو در گام چهارم پژوهش **(فصل پنجم)**، از دو نوع داده‌ی کیفی برای بررسی این جنبه‌ها استفاده شد. نخست از ۴۰ کارشناس درخواست شد که راهکارهای ULRP را امتیازدهی کنند. دوم، به منظور تفسیر نتایج با مشاهدات میدانی و همچنین ارزیابی موانع و پیچیدگی‌های خاص احیای دریاچه‌ی ارومیه سه بازدید از حوضه به عمل آمد. نتایج به دست آمده تعدادی از چالش‌های پیش رو در اجرای ULRP را پررنگ کردند. از جمله نیاز به تقویت قوانین موجود توسعه و مصرف منابع آب و بازنگری در آن دسته از اقدام‌های کشاورزی ULRP که تمرکزشان بر کنترل آب مورد نیاز است. این مرحله همچنین خاطرنشان کرد که مداخلات مهندسی کلان که در حال برنامه‌ریزی هستند، از قبیل جابه‌جایی آب‌های بیناحوضه‌ای، از کمترین سطح پشتیبانی بین کارشناسان برخوردارند. با این همه، اختلاف نظر قابل توجهی میان دانشمندان و سیاست‌گذاران در حمایت از این راهکار وجود مشاهده شد. در حالت کلی این درک وجود دارد که راهکارهایی با هدف کنترل تقاضا، مانند تغییرات الگوی کشت و افزایش بهره‌وری آبیاری عملی‌تر از راهکارهایی با هدف افزایش منابع باشند.

این رساله نشان داد **(فصل ششم)** که رویکرد پایدار به حفظ دریاچه‌ی ارومیه باید از هر دو استراتژی مدیریت تقاضا (با مد نظر قرار دادن پیچیدگی اقتصادی-اجتماعی) و مدیریت تطبیقی منابع (با در نظر گرفتن عدم اطمینان در تغییرات اقلیمی) در یک رویکرد مشارکتی بهره ببرد. در راستای آمادگی برای آینده، باید سناریوهایی نیز برای جریان ورودی کاهش‌یافته به دریاچه‌ی ارومیه، چه به علت تغییرات اقلیمی و چه به علت مدیریت منابع آب، مد نظر قرار گیرند. مدیریت تطبیقی به این معناست که راهکارهای مدیریتی و ساختارهای حکمرانی باید مرتب مورد بازبینی قرار گیرند. این‌گونه است که این اقدامات توانایی مواجهه با میزان قابل ملاحظه‌ای از نامطمئنی در تغییرات آینده‌ی اقلیم و شرایط اقتصادی-اجتماعی را به دست می‌آورند.

در نگاه کلی، این پژوهش با رویکردی بیناحوزه‌ای به چالش حفظ منابع طبیعیِ در معرض خطر با در نظر گرفتن تغییرات اقلیمی مختلف، توسعه‌ی منابع آبی و سناریوهای اقتصادی-اجتماعی ارزیابی پرداخته است. این مطالعه همچنین با ترکیب ارزیابی کمّی مبتنی بر سناریوها و ارزیابی کیفی، تصویر همه‌جانبه‌تری از وضعیت موجود و آینده به وجود آورده است. رویکرد و نتایجی که در این پژوهش ارایه شد، نه‌تنها می‌توانند به حفظ دریاچه‌ی ارومیه کمک کنند، بلکه قادرند در آن دسته از پژوهش‌های بیناحوزه‌ای مشارکت داشته باشند که برهم‌کنش اثر تغییر اقلیم، مصرف آنتروپوژنیک آب و نیاز زیست‌محیطی را مورد توجه قرار می‌دهد؛ به‌ویژه در مناطق (نیمه)خشک.

In the media…

BBC Persian made a short video based on the article in Science of the total Environment (Chapter 3) on 23rd April, 2016 with the following title and summary:

گرمایش زمین، تهدیدی جدی برای آینده بزرگترین دریاچه ایران
تغییرات اقلیمی شرایط دریاچه ارومیه را بدتر می کند. این نتیجه تحقیقاتی است که به تازگی در دانشگاهی در هلند به سرپرستی یک محقق ایرانی انجام شده است. این محققان می گویند تغییرات اقلیمی نه تنها این دریاچه که کم آبی در تمام منطقه را بیشتر خواهد کرد

Natur, 25 April 2016, Germany
Der Urmiasee im Iran droht auszutrocknen, Iran: Ein zweiter Aralsee
Dem Urmiasee im Nordwesten des Iran droht das gleiche Schicksal wie dem Aralsee: Schon jetzt ist seine Wasserfläche enorm geschrumpft und das einst fischreiche Wasser hat sich in eine salzige Brühe verwandelt. Der Klimawandel könnte alles nun noch schlimmer machen, warnen Forscher.

Radio88, 15 November, 2016, Hungry
Eltűnőben a világ egykor második legnagyobb sós tava
Nagyobbrészt a klímaváltozás miatt zsugorodott össze az iráni Urmia-tó, amely egykor a világ második legnagyobb sós tava volt – derül ki az osztrák székhelyű Alkalmazott Rendszeranalízisek Nemzetközi Intézetének tanulmányából.

Der standard, 14 November 2016, Austria
Wasserverbrauch und Klimawandel dörren Urmia-See im Iran aus
Klimawandel zu 60 Prozent dafür verantwortlich, Wasserentnahme zu 40 Prozent

Japan press network: 28 April, 2016, Japan
Climate change threatens Iran's great salt lake

R&D Magazine, 22 Apr 2016, USA
Climate Change Threatens Iran's Great Salt Lake

ND TV, 15 Nov, 2016, India
Climate, Humans Caused Decline Of Once 2nd Largest Salt Lake Urmia

United Press International, 10 November, 2016
World's former second-largest hypersaline lake is almost dry

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Curriculum Vitae

Somayeh Shadkam was born on January 11th, 1980 in Mashhad, Iran. She graduated from the National Centre for Developing Exceptional Talents in 1998. She did her Bachelor of Science (B.Sc) and Masters of Science (M.Sc) degrees in Agricultural Engineering, Irrigation and Drainage Engineering at Ferdowsi University of Mashhad, Iran. Keeping with her main area of interest—water management in situations of water scarcity—she comprehensively researched the environmental impact of irrigation with wastewater during her master thesis. She also advanced her practical skills about irrigation and drainage systems as part of her job as an Irrigation and Drainage Engineer for the Kavosh-Pei Company, Mashhad, Iran. Later, she worked for the IRAN Renewable Energy Organization, Ministry of Energy as Environmental Expert for three years, where she advanced her skills in quality and quantity water resource modelling and developed her understanding of the institutional and practical aspects of water management. She later finished a Master of Engineering (M.E) at Auckland University, Auckland, New Zealand with a First Class Honour. She started her Ph.D at Water System and Global Change group, Wageningen University in 2011. Her Ph.D assessed climate and anthropogenic impacts on environmental flow of Urmia Lake, a highly degraded hyper-saline lake in north-western Iran. In addition, her thesis assessed the effectiveness of policies aiming to restore and preserve the Lake. During her Ph.D, she had several meetings with the Urmia Lake Restoration Program committee also with the farmers and other stakeholders in Urmia Basin about the results of her study. From Jun 2016, she started to work at The International Institute for Applied Systems Analysis (IIASA), Vienna, Austria, as a Research Assistant for the Water program and Exploratory and Special Projects.

Peer-Reviewed Publication

SHADKAM, S., LUDWIG, F., VAN OEL, P., KIRMIT, Ç. & KABAT, P. 2016. Impacts of climate change and water resources development on the declining inflow into Iran's Urmia Lake. *Journal of Great Lakes Research*, 42**,** 942-952.

SHADKAM, S., LUDWIG, F., VAN VLIET, M. T., PASTOR, A. & KABAT, P. 2016. Preserving the world second largest hypersaline lake under future irrigation and climate change. *Science of The Total Environment*, 559**,** 317-325.

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The SENSE Research School declares that **Ms Somayeh Shadkam Torbati** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 44.6 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2012)
- Research in context activity: 'Co-organising WIMEK/SENSE Symposium on Water & Energy Cycles at Multiple Scales' (2012)

Other PhD and Advanced MSc Courses

- High impact writing in science, Wageningen University (2015)
- Survival guide to peer review, Wageningen University (2015)
- Scientific writing, Wageningen University (2013)
- IMPACT2C Summer School 2013, IMPACT2C (2013)
- Downscaling climate projection, Technical University of Denmark (2012)
- Programming in C, PTR - People, Training, Results (2011)

Management and Didactic Skills Training

- Organising Wageningen team field visits to Iran's Ministry of Agriculture, Iran's Ministry of Water and Energy, Sharif University and Urmia Basin, including two half a day round table discussions (2016)
- Co-authoring concept notes for cooperation between Iran and Wageningen and between Urmia Lake Restoration Program and Wageningen (2016)
- Writing press releases 'Climate change threatens already volatile Urmia Lake' and 'Climate and human influence conspired in Lake Urmia's decline', and giving interviews about them (2016)
- Assist in teaching course 'Introduction to global change', Wageningen University (2013 and 2014)
- Supervising MSc student with thesis entitled 'Water Level Reduction and the Adaptation Challenge: the case of Urmia Lake, Iran' (2013)

Oral Presentation

- *Preserving the World Second Largest Hypersaline Lake Under Future Irrigation and Climate Change.* IDRiM 2016 7th International Conference on Integrated Disaster Risk Management Disasters and Development: Towards a Risk Aware Society, 1-3 October 2016, Isfahan, Iran

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