Shahrooz Mohajeri
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Wolf Raber *Editors*

Standing up to Climate Change

Creating Prospects for a Sustainable Future in Rural Iran

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Preface

In Iran, climate change combined with low adaptation capacity and poor resource management strikes with unparalleled force on ecosystems as well as human livelihoods. This book focuses on central Iran and zooms into the Roodasht region, a region in the lower reaches of the Zayandeh Rud river, suffering from increasing water scarcity and, with it, desertification, environmental degradation, loss of livelihood, social tensions, and emigration. The Roodasht region stands out as an example for many arid regions in the world where the rural population has to cope with challenges caused by internal and external factors.

The individual chapters of this edited volume present different approaches of collecting and combining relevant information about the specific problems—qualitative and quantitative research methods like interviews, participatory methods, ground surveys, field tests, and satellite monitoring—and different problem areas that are or can be affected, like agricultural and production patterns, water rights and water use, organizational structures, and political and administrative frameworks. In doing so, we show how the combination of various disciplines and approaches can lead to the development of solutions for sustainable water and land management. It is demonstrated how researchers and practitioners can work in different cultural contexts and adjust general methods to local conditions. We hope the book is a useful tool and reference work for researchers and practitioners in the Middle East and arid regions in general. On the one hand, the book sketches out a state of scarcity of resources and identifies the conflicts many regions may face in the future if no serious counteractive measures are taken. On the other hand, the book provides examples of how various challenges regarding land and water management in rural arid regions can be analyzed and solved.

The authors are international scientists, NGO members, and government officials, converging their specific knowledge in order to create a bridge between research and practical implementation. Their work is not only an important supplement to know-how on the issues of climate change and desertification but also raises public awareness and enables knowledge transfer between several areas and disciplines.

However, it is now fundamentally important that the material in this book be researched further, highlighted in political decision-making, and referenced in regions and countries with similar environmental conditions: a tipping point has already been reached; it is time to act now.

Berlin, Germany

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Chapter 1
Standing Up to Climate Change: Creating Prospects for a Sustainable Future in Rural Iran

Ali Asghar Besalatpour, Lena Horlemann, Wolf Raber, and Shahrooz Mohajeri

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1.1 Introduction

Climate change is the mega topic of the twenty-first century and usually described as any change in climate over time, it is due to natural changes or human activities (IPCC 2014; World Bank 2017; Lange 2019). This definition differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), which defines the term climate change as a change of climate, directly or indirectly attributed to human actions that changes the composition of the global atmosphere and which is, in addition to natural climate variability, observed over comparable time periods (NCCO 2017; IPCC 2018). Climate change is certainly accelerated by the increase in greenhouse gas concentrations, which originates mainly from the combustion of fossil fuels. Global warming as the main effect of climate change has led to rising sea levels, changes in storm patterns, altered ocean currents, changes in rainfall, the melting of glaciers, more extreme heat events, fires, and drought. The Intergovernmental Panel on Climate

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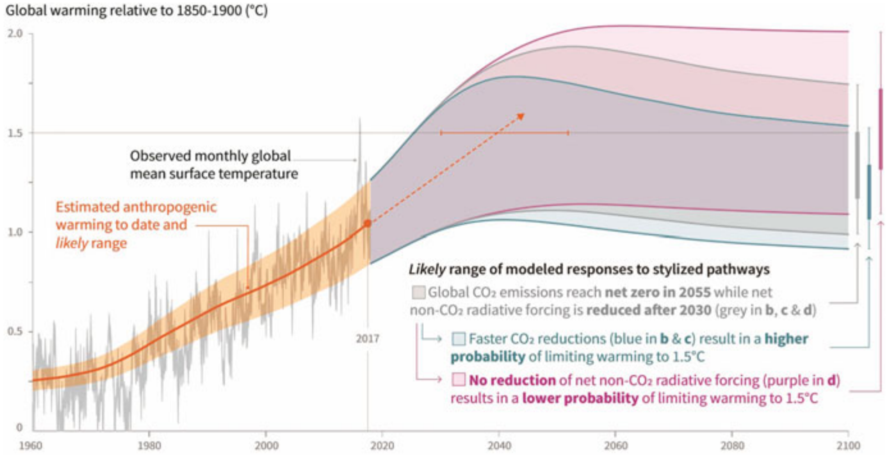

Fig. 1.1 Observed monthly global mean surface temperature (GMST, gray line up to 2017, from the HadCRUT4, GISTEMP, Cowtan–Way, and NOAA datasets) change and estimated anthropogenic global warming (solid orange line up to 2017, with orange shading indicating assessed likely range) (source: IPCC 2018) [Orange dashed arrow and horizontal orange error bar show respectively the central estimate and likely range of the time at which 1.5 °C is reached if the current rate of warming continues. The gray plume to the right of panel shows the likely range of warming responses, computed with a simple climate model, to a stylized pathway (hypothetical future) in which net CO_2 emissions decline in a straight line from 2020 to reach net zero in 2055 and net non-CO_2 radiative forcing increases to 2030 and then declines. The blue plume in panel shows the response to faster CO_2 emissions reductions, reaching net zero in 2040, reducing cumulative CO_2 emissions. The purple plume shows the response to net CO_2 emissions declining to zero in 2055, with net non-CO_2 forcing remaining constant after 2030. The vertical error bars on the right of panel show the likely ranges (thin lines) and central terciles (33–66 percentiles, thick lines) of the estimated distribution of warming in 2100 under these three stylized pathways (data from the Global Carbon Project) (source: IPCC 2018)]

Change (IPCC) has identified and characterized scientifically global causes and impacts of climate change since 1990. Their latest report again highlights exacerbated land degradation, desertification, expansion of arid climate zones, intensified dust storms and threats to food security, human health, and economic activities as dramatic impacts of climatic change particularly in arid and semiarid regions (IPCC 2019).

For three years in a row now, the World Economic Forum Global Risk Report identifies climate change and related environmental impacts as the standout long-term risks the world faces (World Economic Forum 2019). According to the Fifth Assessment Report of IPCC (AR5), the warming of the climate system is unequivocal (see also Fig. 1.1 taken from the Summary for Policymakers). With regard to particular changes in frequency and intensity of precipitation, numerous studies indicate that global warming is leading to a deterioration of the ecosystem and development of a water crisis (Falkenmark and Rockström 2006; Zuo et al. 2015). This process exacerbates water scarcity, particularly in dry and semidry regions and intensifies spatial and temporal variabilities of water resources on basin level (Milly et al. 2005; Vörösmarty et al. 2010; Dastorani and Poormohammadi 2016). Murphy and Ellis (2017) point out the particular vulnerability of watersheds by showing that watershed climate is more sensitive to climate change than other areas. In addition, Huang et al. (2016) show that global semiarid regions have grown enormously over a 60-year scope. Many sectors suffer from direct or indirect effects on the economy due to the high variation and decline in rainfall in dry and semidry areas, which again leads to a loss of livelihoods (Anyamba et al. 2014) and, most likely, affects surface water variation (Chiew et al. 2009).

Mitigating climate change would require substantial and sustained reductions in greenhouse gas (GHG) emissions. Strategies for mitigation and adaptation to climate change need to be underpinned by common enabling factors like effective institutions and governance, adequate funding, innovation, and investments in environmentally sound technologies and a revision of the build infrastructure. It is therefore vital for all countries, especially those in arid and semiarid regions, to take mitigation and adaptation measures simultaneously.

1.2 Climate Change Perspectives in the MENA Region

The adverse effects of climate change affect all countries. Countries in the Middle East and North Africa (MENA) region (Fig. 1.2) are particularly vulnerable to persistent droughts, rising sea levels, threatening food security, water and energy supplies, and health (see an overview of developments and challenges resulting from climate change in the MENA region by Ribbe and Denavi in this volume; Verner 2012; Wodon et al. 2014; Göll 2017; Waha et al. 2017; World Bank 2017). MENA is the most water scarce region in the world. According to a recent World Bank report, over 60% of the MENA region's population lives in areas with high or very high

Fig. 1.2 The Middle East and North Africa (MENA) region (Source: World Bank 2017)

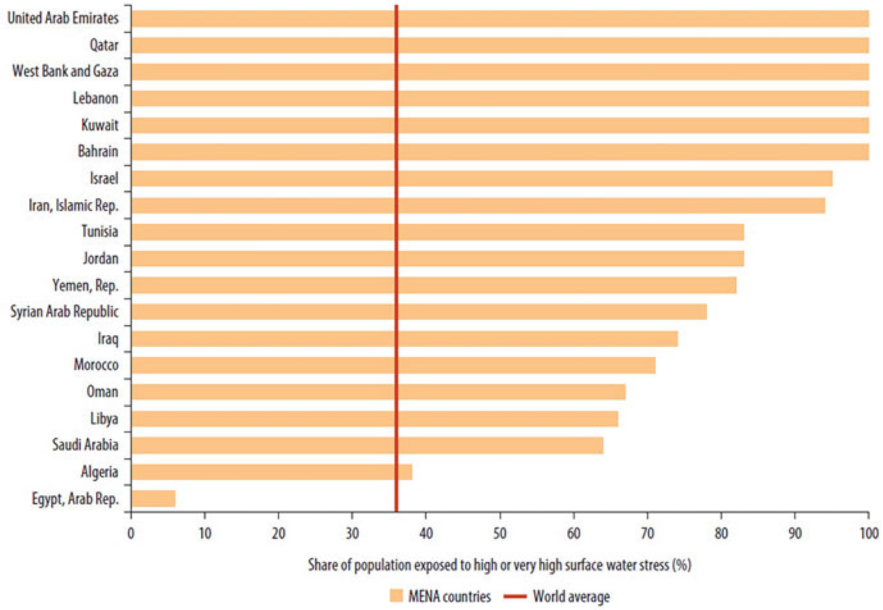

Fig. 1.3 Population (%) exposed to high or very high surface water stress, by country and economy, 2010 (Source: World Bank 2017) [Areas where water withdrawals are 40% or more of surface water supplies are considered to have high or very high stress. Caution should be used in comparing data on annual freshwater withdrawals, which are subject to variations in collection and estimation methods. In addition, inflows and outflows are estimated at different times and different levels of quality and precision, requiring caution in interpreting the data. This calculation does not account for water stress arising for upstream developments that may cause shortages in downstream countries and economies (World Bank 2017).]

surface water stress with reduced available amounts of water for immediate uses such as agriculture or filling reservoirs for drinking water (World Bank 2017) (Fig. 1.3). Over 70% of the region's gross domestic product (GDP) is generated in areas with high to very high surface water stress (World Bank 2017). The region would be severely affected by a global warming of 2 °C and even more of 4 °C, particularly because of the increase in projected heat extremes, the consequent reduction in water availability and the expected negative consequences for regional food security (Fig. 1.4) (World Bank 2014).

Due to the changing precipitation patterns, water insecurity and projected sea level rise, the region will face major challenges, particularly in the areas of agriculture, water, and food security (Göll 2017). These biophysical effects, coupled with other pressures and a lack of resilience in some countries in the region, will likely cause high vulnerabilities in these sectors and for social dimensions (Waha et al. 2017).

The MENA region is water scarce, and most of the land area receives less than 300 mm of annual rainfall (200–300 mm is the lower limit for rain-fed agriculture).

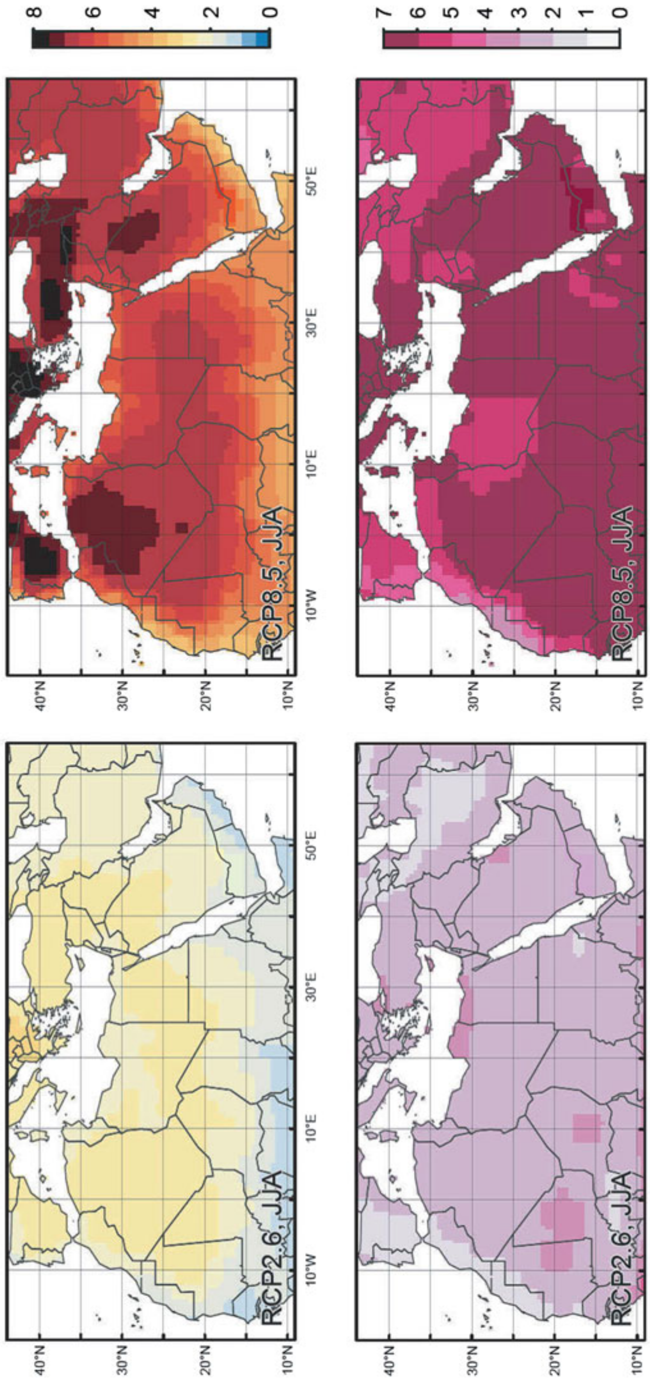

Fig. 1.4 Multi-model mean temperature anomaly for RCP2.6 (2 °C world, left) and RCP8.5 (4 °C world, right) for the Middle East and North African region [Temperature anomalies in degrees Celsius (top row) are averaged over the time period 2071–2099 relative to 1951–1980 and normalized by the local standard deviation (bottom row) (World Bank 2014)]

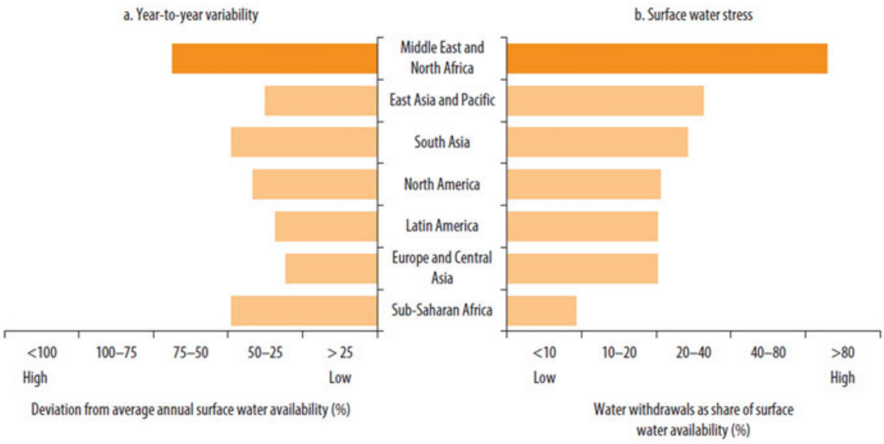

Fig. 1.5 Water stress and year-to-year variability in surface water, by world region (World Bank 2017) [Water stress measures total water withdrawals as a percentage of total surface water availability. It does not account for dependence on transboundary water sources or nonconventional water sources. Year-to-year variability measures the percent deviation from mean annual surface water availability. (World Bank 2017)]

The annual availability of renewable water resources is below 1000 m^3 per capita in most countries (World Bank 2014). Given the current situation of water scarcity and a lack of arable land, climate change would put further pressure on water resources, agriculture, and food security (World Bank 2014, 2017; Göll 2017; Waha et al. 2017; Lange 2019). In addition, the strong variability from year-to-year in the region is prone to multi-year droughts and intense rainfall events, which can lead to destructive flooding (Fig. 1.5).

The agricultural sector, of which 70% is entirely rainfed, is also exposed to strongly changing climatic conditions (Waha et al. 2017). A warmer and drier climate is expected to shift the vegetation and agricultural zones to the north, and lower rainfall and higher temperatures will presumably shorten wheat growing periods in large parts of the region by about 2 weeks by the middle of the century (2031–2050) (World Bank 2014). It is expected that crop yields in parts of the MENA region will decrease by 30–60% without taking adaptation into account. Reductions in crop productivity are expected by mid-century. Legumes and maize crops are expected to be worst affected as they are grown during the summer (World Bank 2014). Climate change will affect animal production in a number of ways, including changes in the quantity and quality of available feeds, changes in the length of the grazing season, additional heat stress, reduced drinking water, and changes in livestock diseases and disease vectors (World Bank 2014). This is crucial as the agriculture sector is the largest employer in many MENA countries and makes a significant contribution to the national economy. Increasing food and water demands pose even greater risks to the region's prosperity, as the population is expected to double by 2070 (Waha et al. 2017).

Natural climate variability and global warming can influence precipitation patterns around the world, contributing to desertification. On the one hand, a decrease in precipitation means that soils dry out and become more susceptible to erosion (Smith et al. 2017). Furthermore, heavy rainfall itself may erode soil and cause waterlogging and ground subsidence. The MENA region is largely threatened by dust storms that threatens people's health, agriculture, and the economy.

With additional pressure on already scarce resources and the intensification of existing threats such as political instability, poverty, and unemployment, climate change could act as a threat multiplier in the region. This can create the conditions for social uprising and violent conflict. The MENA region is already characterized by very high summer temperatures, making the region's populations highly susceptible to further temperature increases. The deterioration in livelihoods in rural areas can contribute to internal and international migration and further burden urban infrastructure and the associated health risks for poor migrants. Migration and climate-related pressure on resources might increase the risk of conflict (World Bank 2014). Establishing a direct link between climate change and conflicts is challenging due to several factors and conflicting conclusions and methods. Further research is needed to investigate and determine the relationship between climate change and conflict and to relate long-term climate change to migration and social conflicts.

1.3 Climate Changes Perspectives in Iran

Iran is a typical example of a MENA region that is particularly affected by climate change. About 52% of the country consists of mountains and deserts and 16% are higher than 2000 m above sea level. More than half of Iran's land consists of mountains, with a quarter being plains and deserts and less than a quarter being arable land (FAO 2008). As depicted in Fig. 1.6, Iran lies in a belt of regions with

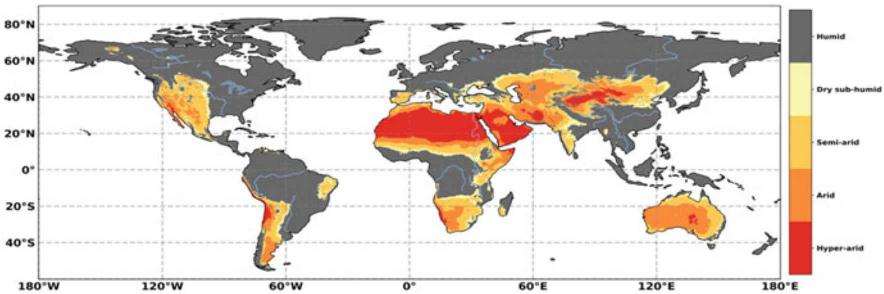

Fig. 1.6 Geographical distribution of drylands delimited based on the aridity index (AI) (Mirzabaev et al. 2019) [The classification of AI is: Humid AI >0.65, Dry sub-humid $0.50 < AI \leq 0.65$, Semiarid $0.20 < AI \leq 0.50$, Arid $0.05 < AI \leq 0.20$, Hyper-arid AI <0.05. Data: Terra Climate precipitation and potential evapotranspiration (1980–2015)]

arid and hyper-arid conditions. Apart from the coastal areas, the temperature in Iran varies between 22 °C and 26 °C, and the average annual precipitation is around 240 mm. Total precipitation provides 417 BCM of water, of which 300 BCM (72%) evaporate. In addition to the 117 BCM of available water, 13 BCM flows into the country from neighboring countries through rivers, making 130 BCM of water available (Iran's Third National Communication to UNFCCC, NCCO 2017).

Iran has recently taken more decisive measures to adapt to and mitigate climate change, based on Article 50 of its Constitution, to insure legal protection of the environment. Forward to international cooperation: Iran presented Initial and Second National Communications to the UNFCCC in 2003 and 2011, respectively. In this ongoing process, the Third National Communication (TNC) to UNFCCC also fulfills the country's commitment as a Non-Annex I Party to the Convention, to prepare and present the Convention with updated reports on national GHG emission inventory,[1] national GHG mitigation policies, vulnerability, and adaptation, national strategies, a Global Climate Observation System (GCOS), research and education and economic assessments (NCCO 2017). Iran's National Climate Change Office (NCCO), among other tasks (including raising public awareness and national coordination of the Sub-committee for Sustainable Development), has built national capacities to systematically address climate change thorough measures such as providing Iran's Low-carbon Economy Document, Intended National Determined Contribution (INDC), and the National Strategic Plan on Climate Change. All these measures necessitated a considerable amount of duly recognized effort in providing these inputs (NCCO 2017).

A recent study on long-term changes in maximum, minimum, and average temperature and changes of precipitation in the country reveal that Iran will experience an average temperature rise of 2.6 °C and rainfall decrease of 35% over the next few decades (Daneshvar et al. 2019). Both temperature and precipitation variabilities can influence rainfall patterns, water resources, and agricultural activities, which can lead to droughts and floods and thus desertification and dust storms (Vaghefi et al. 2019).

1.3.1 The Water–Food–Health Nexus

Based on the literature review, the main impacts of climate change on Iran's water resources are rising temperatures, changes in rainfall patterns, less snow cover and an increased likelihood of floods and droughts (Abbaspour et al. 2009; Hashemi 2015; Afshar and Fahmi 2019; Vaghefi et al. 2019). Madani (2014) highlights water crises in Iran, including depleting groundwater levels, the drying out of lakes, the water supply, and extreme weather events. In connection with administrative problems, Iran has faced many disasters, including a significant number of shrinking

[1] As of 2014, Iran was the seventh largest CO_2 emitter with 649,481 Kilotons CO_2/year.

lakes and dry rivers that had led to land subsidence, floods,[2] and droughts. Lake Urmia—the largest lake in the Middle East and one of the largest hypersaline lakes in the world—has shrunk considerably and may completely dry up in 6 to 9 years (Vaghefi et al. 2019). Hamun Lake in eastern Iran, Parishan and Shadegan lakes in the south, and Zayandeh Rud river in central Iran are also at risk of disappearing due to mismanagement and climate change. The study by Abbaspour et al. (2009) stated that groundwater recharge in regions with already scarce water resources will decrease by up to 50–100% in the eastern part of the country. Future analyses of extreme dry periods in Iran show a significant 16-fold increase in most of the country, south of the Alborz Mountain chain (Fig. 1.7).

The World Bank (2017) report also indicates an increased surface water stress due to climate change in countries like Iran, which are in a politically and ecologically fragile situation (see Fig. 1.8). The Blue Water Sustainability Index created by The World Bank (2017) for the MENA region expresses that most of Iran's water consumption is covered by unsustainable extraction (see Fig. 1.9). The results of a study by Besalatpour et al. on blue water and green water resources changes in a basin in central Iran (Zayandeh Rud river basin) are presented in Chap. 6. The authors' findings show that the green water flow component in the eastern part of the catchment is relatively increased due to the influence of climate changes in the past. Their results indicate that, in general, the amounts of blue water and green water storage were greater in the western part of the study area than the eastern parts. The authors' findings provide valuable information about the spatial (in sub-basin scale) and temporal (annual and monthly) distribution of water resources which can be useful for long-term planning and optimal management of the study area.

Based on the report from Iran's Third National Communication to UNFCCC, published by the NCCO, the impacts of climate change on Iran's water resources for the period 2015–2030 compared to the period 1982–2009 can be summarized as follows (NCCO 2017):

- The evaporation volume of the country increased by 27.3 BCM due to the increase of two degrees in temperature.
- Recharge of the groundwater decreased by 20%, due to the increase of two degrees in temperature.
- Snowfall reduced by 5% and snowmelt time shift by 1 month. Also, the snow level increased to 200 meters. This trend will continue in the future.
- The likelihood of severe droughts and severe floods will increase in the future.
- Precipitation trends that are less than 5 mm and 10 mm will continue to decrease.
- According to the pessimistic scenarios, runoff changes are decreasing in all basins.

[2]From 2015 to 2018, approximately six major floods occurred in unexpected regions located in arid and semiarid parts of Iran. In addition, floods in the northern edge of the country often cause substantial damage. The worst flooding disaster occurred in August 2001, where a once in 200-year-flood affected more than 27,000 people, rendered 10,000 homeless, and killed about 250 people in Golestan Province in northern Iran (Vaghefi et al. 2019).

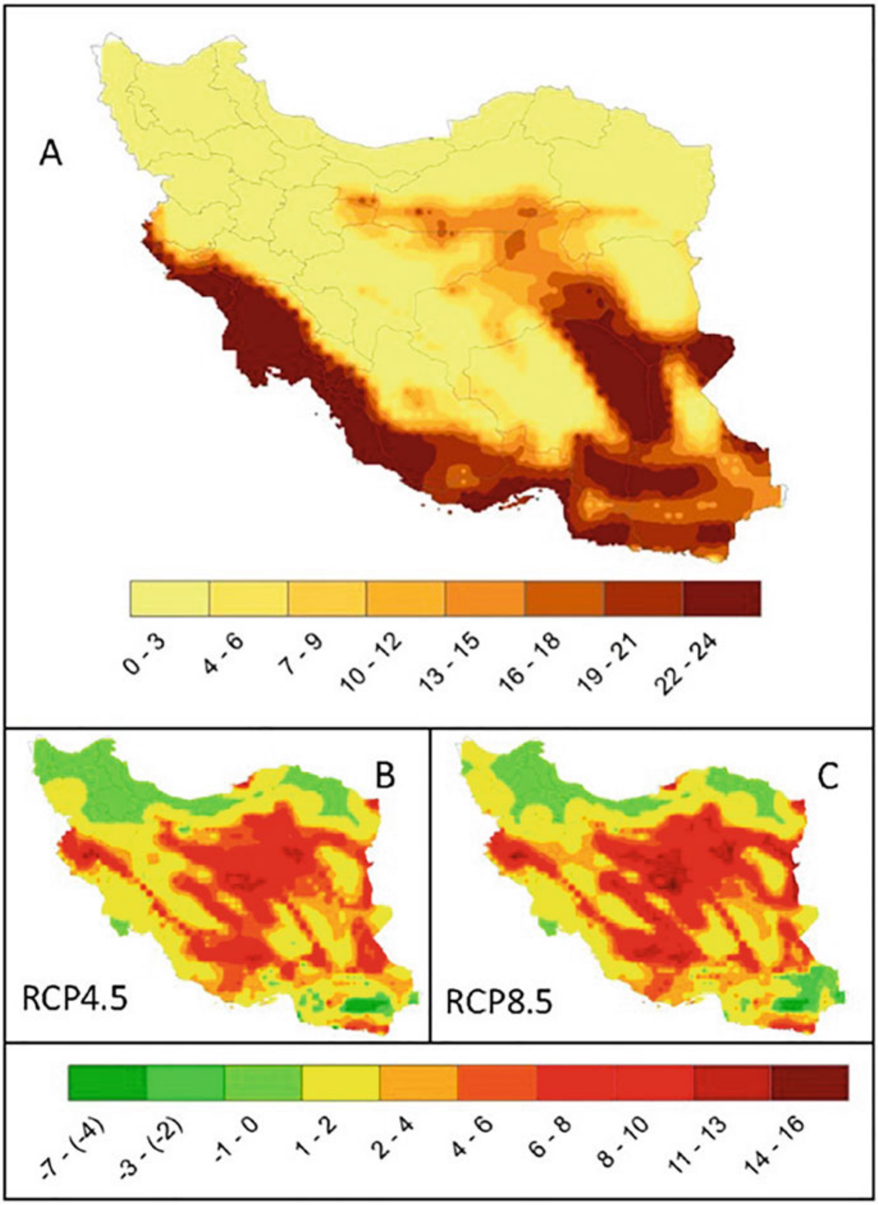

Fig. 1.7 Compound analysis for dry periods where (for ≥120 consecutive days, rainfall <2 mm day−1 and Tmax ≥30 °C) (Vaghefi et al. 2019) [(A) shows the frequency of such conditions in the past (1980–2004). (B, C) Illustrate the difference between the historical and the future (2025–2049) frequencies of the events. Increasing extreme dry periods are predicted for hot dry desert and hot semi-desert areas, while the Caspian Sea's mild and wet zone may experience fewer extreme dry conditions in both scenarios]

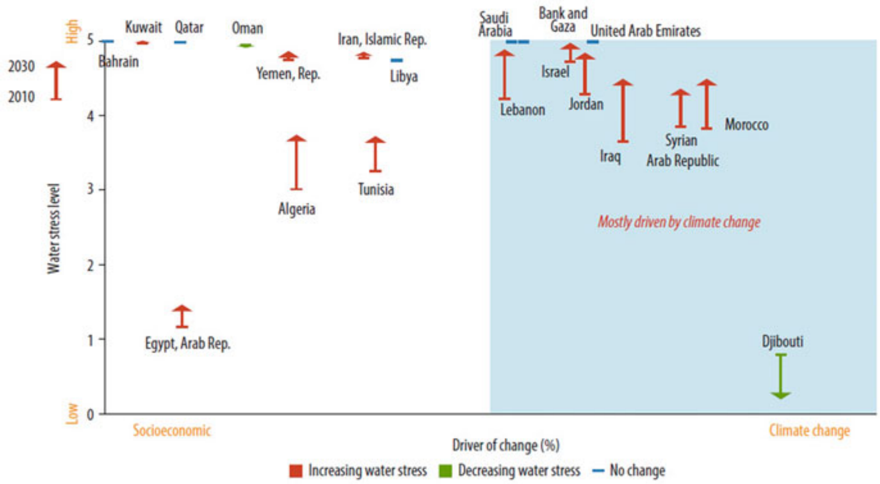

Fig. 1.8 Future drivers of surface water stress in the Middle East and North Africa (World Bank, 2017) [Water stress is quantified as the ratio of annual water withdrawals to average annual surface water availability under an RCP 8.5 (high emission scenario) and SSP2 (business as usual for a socioeconomic change). The position of each country along the horizontal dimension reflects the percent change in water stress, which is driven by climate change (right) or socioeconomic change (left). Future climate change is modeled using an ensemble of climate models for a high emission scenario (RCP 8.5). Socioeconomic change is modeled using a middle-of-the-road scenario where future socioeconomic trajectories do not shift markedly from historical patterns (that is, a business-as-usual scenario for population growth and the economy). Estimates of surface water stress do not account for withdrawals from groundwater and nonconventional water supplies (World Bank 2017)]

- Unsafe drinking water supply in most major cities in the future.
- Warmer and more humid conditions increase the spread of diseases in the tropical regions.

In order to be able to feed a growing population of currently 82 million Iranians, scarce water resources must be managed effectively. Given the dynamic of land degradation and desertification facilitated by climate change, it is evident that sustainable management mechanisms must be used to avoid persistent land degradation. In this regard, spatial planning and integrated management of water resources; promoting the productivity and a comprehensive approach to managing water resources; improve efficiency and sustainability in the use of shared water resources in close cooperation with neighboring countries; consideration of the economic, security, political, and environmental values of water in order to achieve a desirable use, supply, maintenance, and consumption need to be considered (NCCO 2017).

In Iran, the agricultural sector accounts for about 18% of GDP. Previous studies show that Iran's total crop yield is expected to decrease in all climate change scenarios. However, the extent of the changes in yield depends on the type of

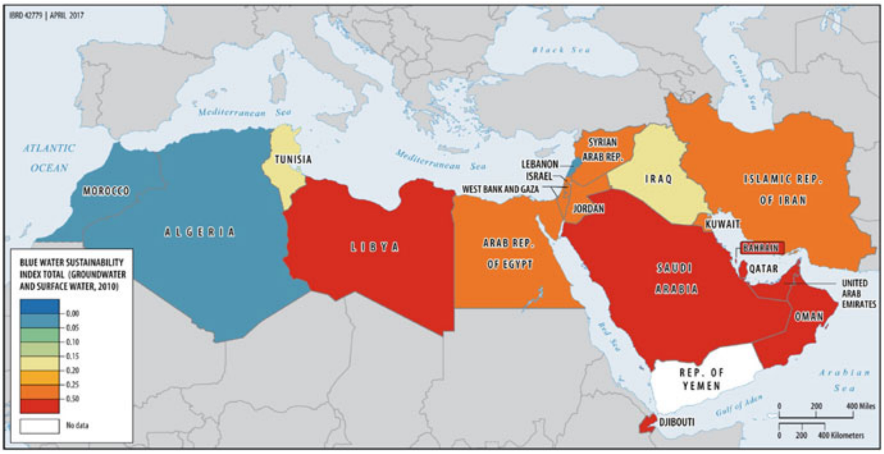

Fig. 1.9 Blue Water Sustainability Index, Middle East and North Africa, 2010 (World Bank 2017) [The BlWSI is a dimensionless quantity ranging from 0 to 1 that expresses the portion of consumptive water use that is met from non-sustainable water sources. Blue = sustainable; red = unsustainable. Non-sustainable surface water use is estimated as the amount of environmental flow requirements not satisfied due to surface water over-abstraction. Non-sustainable groundwater use is estimated as the difference between groundwater abstraction and natural groundwater recharge plus recharge from irrigation return flows (World Bank 2017)]

crop, the assumptions regarding the CO_2 fertilization effect, the climate scenarios, and the possibilities for adaptation (Karimi et al., 2018). The rise in mean yearly temperature, especially in winter, could also extend the growing season. The NCCO (2017) report shows that the net irrigation needs of irrigated wheat and alfalfa will increase, while it will decrease for irrigated forage corn in most parts of the country during the period 2016–2030. The potential yields of irrigated wheat, alfalfa, and forage corn will also decrease in most parts of the country over the same period (NCCO 2017). Salemi et al. (Chap. 15 of this volume) calculate the water demands of autumn and spring plants using the example of the eastern region of the Zayandeh Rud river basin in central Iran. They show how the optimization of computer algorithms and the establishment of a sound database of net water requirements and related maps can support decision-makers in developing sustainable agricultural sector strategies.

The Communication to the UNFCCC (NCCO 2017) presents various possible solutions to effectively deal with these important consequences of climate change, ranging from sustainable soil and water management to socioeconomic policies for reducing poverty in rural areas. Involving farmers in the conservation of water and soil resources and combating the effects of climate change is crucial.

1.3.2 Desertification, Salinization, and Dust Storms

Climate variability and anthropogenic climate change, both leading to an increase in air temperature on the land surface and evapotranspiration and a decrease in precipitation, have played a role in desertification in Iran in interaction with human activities such as overuse of water (Emadodin et al. 2019). Desertification and climate change are expected to reduce the productivity of crop and livestock, change the composition of plant species, and reduce biological diversity in dry and semi-dry areas (Mirzabaev et al. 2019; Emadodin et al. 2019). It is reported that around one million km^2 of land is at risk of desertification (Jafari and Bakhshandehmehr 2013; Emadodin et al. 2019). In Chap. 3 of this volume, Amiraslani, and Caiserman shed light on current water management policies in Iran. Several initiatives have been implemented to tackle water shortages in the country, nonetheless, these measures have not been sufficient to address the environmental challenges of the dimensions that exist in Iran. The relevant question remains what kind of strategies of the national level can tackle land degradation and water shortage simultaneously? Using a literature review and employing reliable data and statistics, Amiraslani and Caiserman portray the contemporary situation of water resources in Iran and provide initial answers to the pivotal questions raised.

Climate change as manifested by drought and desertification has led to a substantial increase in dust generation in many arid and semiarid countries as well as in Iran (Moulin et al. 1997; Ekanem and Nwagbara 2005; Middleton 2019). Dust storm frequencies and intensities have increased significantly in recent years (see Fig. 1.10) and have had a huge influence on the economy and environment of Iran and thus on the daily life of Iranian people. At least five million people are directly affected by dust storms, and many more are indirectly influenced by the transfer of sand particles into their habitats (Morabbi 2011; Cao et al. 2015). It should be noted that dust storm sediments in the region are high in salinity and a number of socioeconomic impacts have been identified, including threats to human health (Middleton 2019). Aghasi et al., in Chap. 10 of this volume, assess the origin of annual dusts produced in the Zayandeh Rud River basin in Central Iran and the effects of dry sediments of the Gavkhuni wetland on the regional environment.

1.4 Perspectives on Climate Change in the Zayandeh Rud River Basin

The Zayandeh Rud in Central Iran is one of the country's most important rivers, providing water for more than four million inhabitants. Originating in the Zāgros Mountains at an altitude of about 2300 m, the river passes vast agricultural areas, large scale industry sites and the city of Isfahan, before it ends after about 350 km in the Gavkhuni wetland at an altitude of 1500 m, an area listed by the Ramsar Convention as protected wetlands in 1975 (Fig. 1.11). The basin with an area of

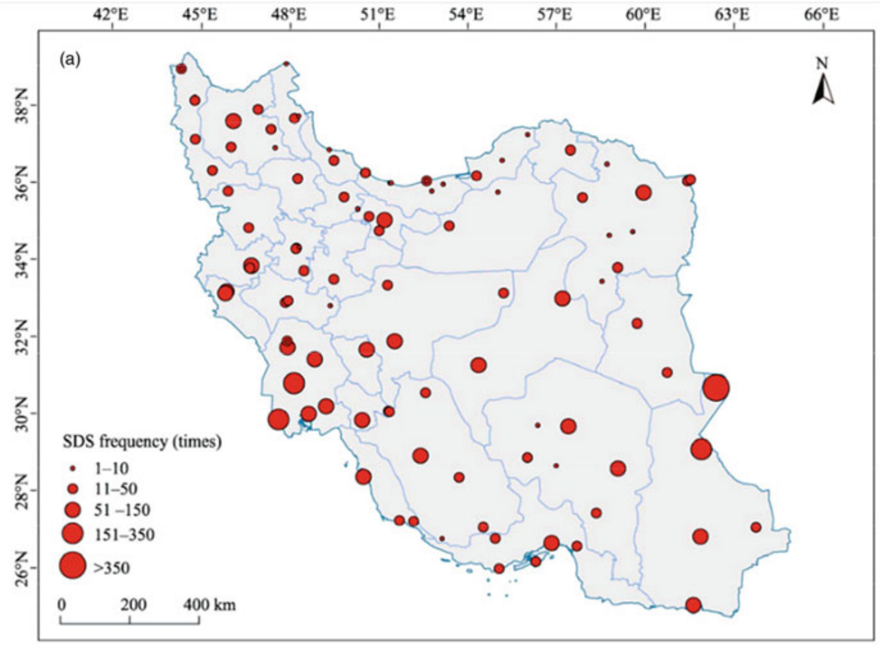

Fig. 1.10 Sand and dust storms frequency map in Iran from 2000–2013 (Source: Cao et al. 2015)

about 27,000 km^2 is located mainly in the Province of Isfahan. It has a predominantly arid or semiarid desert climate with annual precipitation as low as 55 mm in the east, whereas the mountainous western part may be considered as semi-humid with an average annual rainfall of 1500 mm. Rainfall in the basin averages to 265 mm per year with a wet season in winter. Temperatures have always been high in summer at an average of 30 °C and as low as 3 °C during winter (Mohajeri et al. 2016; Mohajeri and Horlemann 2017). Annual potential evapotranspiration makes irrigation necessary for agricultural activities in the main part of the basin (Molle et al. 2004).

The exceptional geostrategic location of the Zayandeh Rud basin has been the driving force for socioeconomic, cultural, and political growth around the city of Isfahan, the former capital of Iran. It has been a hub, not only for culture and trade, but for regional water resources management with interbasin water transfers into the basin, and from the basin to other regions. During the past 60 years, the Zayandeh Rud Basin has enjoyed a flourishing population growth from one to almost four million inhabitants particularly in urban areas. Furthermore, a thriving industry employs more than 300,000 people, and agricultural areas expand up to 225,000 ha, situated mainly in six large irrigation schemes consuming up to 90% of the water in the basin (Mohajeri et al. 2016; Raber 2017).

These developments, and with them the boost of water users, have led to an increasing water demand in the basin. Between 2000 and 2010 2 BCM of water has

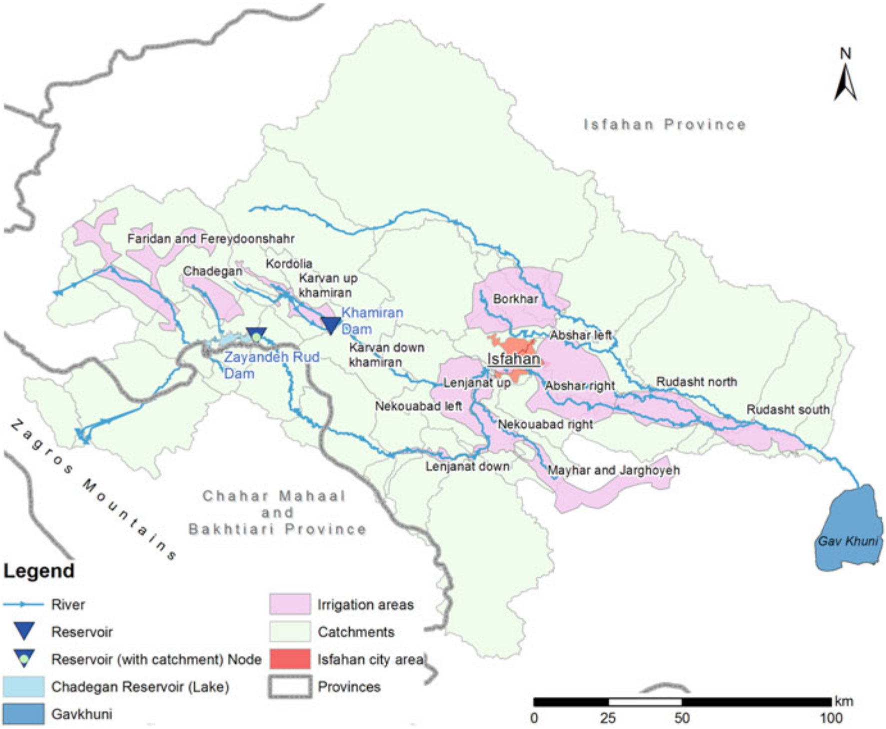

Fig. 1.11 Zayandeh Rud Catchment (Source: Mohajeri et al., 2017)

been used annually in the catchment including water transfers to neighboring provinces, whereas only 533–1720 MCM could be provided by the main Zayandeh Rud reservoir (Torfe et al. 2017). Water distribution patterns are determined by the distribution of legal water entitlements, challenging the historic water distribution rationales. Ziaei (Chap. 4 of this volume) elaborates on how the traditional way of distributing water between farmers is organized—according to the Sheikh Baha'I Scroll that has evolved over the centuries, but is no longer suitable to coping with today's water problems. He shows how the excessive distribution of water entitlements in the past have contributed to today's water crisis and consequential social unrest.

The responses to the deficit in water supply have mostly been technocratic in nature, altering the natural hydrology of the region by extracting more water from other basins. Groundwater resources are intensively exploited, upstream users have taken advantage of their privileged access to water resources and water is being redistributed to urban and industrial users (Molle and Mamanpoush 2012). The rural downstream irrigation networks and the environment in the basin have been the losers of the harsh competition for scarce water resources in the closed basin (Molle et al. 2009). In the lower reaches of the Zayandeh Rud River, most people live from agriculture. In years with sufficient water resources, the local irrigation networks provide water for around 70,000 ha of cultivated area. Together with the Gavkhuni wetland, the Roodasht irrigation network is surrounded by desert and highly affected by climate change impacts (Eslamian et al. 2017). Torfe et al. (2017) indicate that the Gavkhuni wetland has received less than 30 MCM annually between 2000 and 2010, when its natural minimum water requirement is calculated in different studies to be between 70 and 240 MCM. Iranmehr et al. (2015) have analyzed remote sensing data for a 10-year period between 2003 and 2013 and show that more than 40% of the Gavkhuni wetland and Zayandeh Rud ecosystem have declined.

Raber et al. (Chap. 7) present an overview of the complex dynamics of water availability, land-use change, and environmental degradation using the example of the Roodasht region. A vulnerability analysis of farmers towards water scarcity induced by climatic and socioeconomic changes were carried out. The chapter presents its findings with a particular focus on water availability and management in terms of physical appearance, legal aspects, and actual decision-making in the eastern part of the Zayandeh Rud basin. Furthermore, the complex impacts of water management practiced during the past decades on agriculture, water, and soil quality, as well as on ecosystems like the Gavkhuni wetland are analyzed.

The overexploitation of water resources driven by the ideal of socioeconomic growth and everlasting control over natural resources has been and will further be amplified by impacts of climate change in the region, characterized by global warming, less precipitation, higher climate variability, and land degradation (IPCC 2019). Publications that present results from different climatic models all forecast that annual temperature is going to increase by around 1 °C in the basin (Kouhestani et al. 2017) and particularly in the eastern part (Gohari et al. 2013, 2017; Zareian et al. 2016; Eslamian et al. 2017). In Fig. 1.12 Eslamian et al. (2017) present temperature projections for the Zayandeh Rud basin by analyzing 15 Global Climate Models under the A2 and B1 emission scenario of the 2007 IPCC Report. Regarding the projections, they expect a dramatic temperature increase in the arid eastern part of the basin of one to two degrees.

At the same time, researchers forecast that precipitation is going to decrease in the western part of the basin where the Zayandeh Rud has its main source of water (Gohari et al. 2013, 2017; Zareian et al. 2016; Eslamian et al. 2017). Precipitation projections across the whole basin do not indicate a general trend. As presented in Fig. 1.13, the western mountainous part of the basin has a general decreasing trend particularly in winter and springtime. Only the A2 scenario with 25% probability percentiles does not confirm this overall trend. By contrast, precipitation projections for the eastern part of the basin do not show this general decreasing trend, but in this arid part of the basin, annual average precipitation is anyhow as low as 55 mm (Gohari et al. 2017).

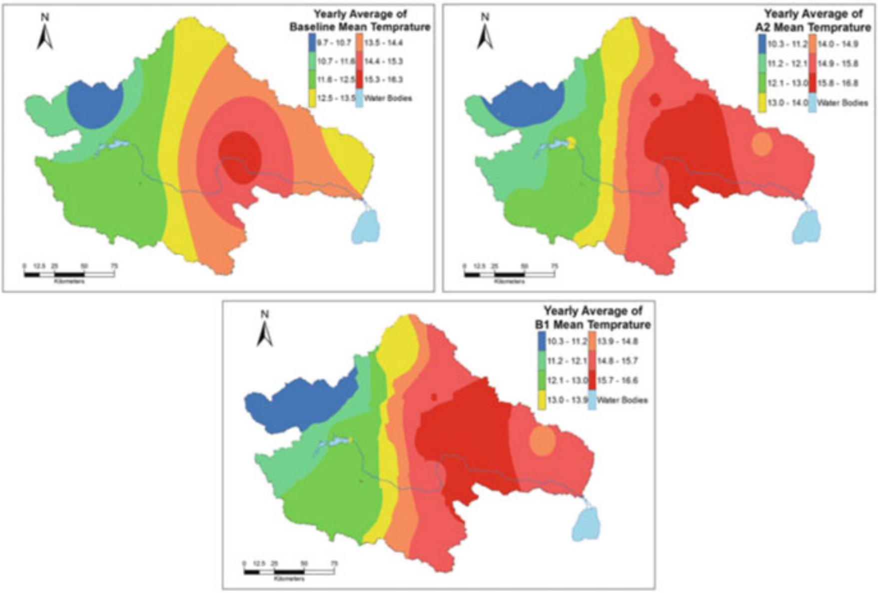

Fig. 1.12 The Zayandeh Rud Basin's annual mean temperature under baseline period (1971–2000) and A2 and B1 climate change scenarios (2015–2044) (Source: Eslamian et al. 2017)

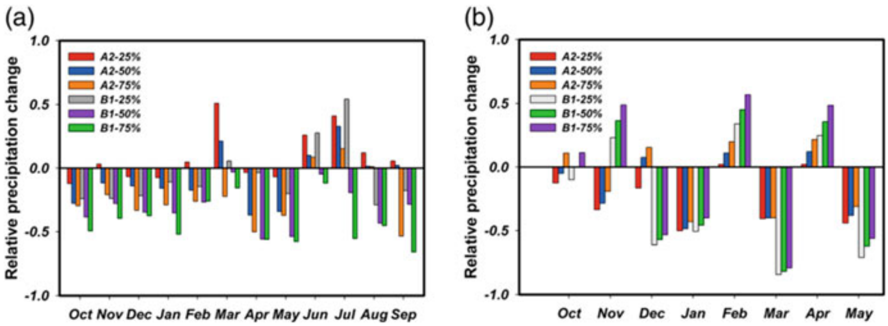

Fig. 1.13 Projected monthly precipitation changes under different climate change scenarios (2015–2044) relative to the baseline period (1971–2000) for: (**a**) the western part of the basin; and (**b**) the eastern part of the basin (June, July, August, and September are not shown due to minimal baseline precipitation levels in the lower sub-basin) (Source: Gohari et al. 2017)

1.4.1 Consequences of Climate Change in the Zayandeh Rud Basin

Climate change-induced drought can cause severe damage to vulnerable ecosystems. Therefore, understanding the implications of climate change on drought is important for water resources management. Naeini et al. (Chap. 5) discuss drought indices calculated for drought duration, severity, and peak intensity in the east Zayandeh Rud Basin for a historical period (1979–2008), the present and the near future (2016–2057), and the distant future (2058–2099) using 15 general circulation models (GCM) from the IPCC Fifth Assessment Report (AR5) scenarios. A significant past drought event in the basin was used as a benchmark with specific severity, duration, and peak intensity. Results from the historical analysis suggest that the return period of significant drought is expected to increase in the future. Also, in some of the GCM's results, drought conditions in the western part of the basin were more severe compared to the eastern part. The characteristics of the projected altered climatic regime in the catchment have severe impacts particularly on agriculture. While warming may potentially shorten the growth period of certain crops, the crop productions of all crops are expected to decrease due to lower precipitation and higher water requirements, resulting from higher temperature (Gohari et al. 2013). Under the A2 emission scenario potential evapotranspiration, a factor for the water demand of crops, would increase by 3.1–4.8% in the basin (Zareian et al. 2016).

Wheat, barley, rice, and corn are popular crops in the basin and account for roughly 55% of the total cultivated area (reference year 2006) (Raber 2017). Gohari et al. (2013) show that these crops have a negative response in terms of yield on the projected climate scenarios for the period between 2015 and 2044. A dry and warm future will reduce wheat production, depending on the climate scenario, by 2.5–20.7%, barley by 1.4–17.2%, rice by 2.1–9.5% and corn by 5.7–19.1%. They argue that, on the one hand, higher temperature causes shorter growing periods resulting in yield loss, and on the other hand, heat increases irrigation water demand. Under most climate change scenarios, these two factors result in a decrease in water productivity as a key figure for the amount of physical production of a crop per unit volume of water used (see Fig. 1.14) (Gohari et al. 2013).

Rising temperatures and scarce water resources lead to another major risk for agriculture: In the basin where each drop of water is used several times along its passage through the river, pollutants, and salts accumulate in the water. Saline water is used for irrigation and due to low applied volumes and high temperatures, water is being evaporated and transpired by plants, salts accumulate in the top layer of the soil, making land unsuitable for agriculture and prone to degradation and desertification. Only 5% of the total land of Isfahan Province is considered arable but shows high soil salinity and low soil organic matter. Particularly the lower part of the Zayandeh Rud is affected by soil salinization and alkalinity (Fathi and Rezaei 2013). Salinity levels of water used for irrigation in Zayandeh Rud vary substantially from EC values of less than 1 dS/m in the upper reaches up to around 6 dS/m with peaks of 19.6 dS/m in the lower reaches (Pourmoghaddas 2006). In Roodasht, soil salinity is reported to be about 14 dS/m with negative impacts on crop yields as field experiments in the area have shown (Salemi et al. 2000).

Remote sensing analysis for a 10-year period between 2003 and 2013 revealed that salt-affected areas have expanded in the basin to more than 90% (Iranmehr et al. 2015). Establishing landscape evolution studies helps to improve the understanding of physical environments in soil-related studies. The objective of Toomanian and Salemi's work presented in Chap. 8 is to depict the historic evolution of the

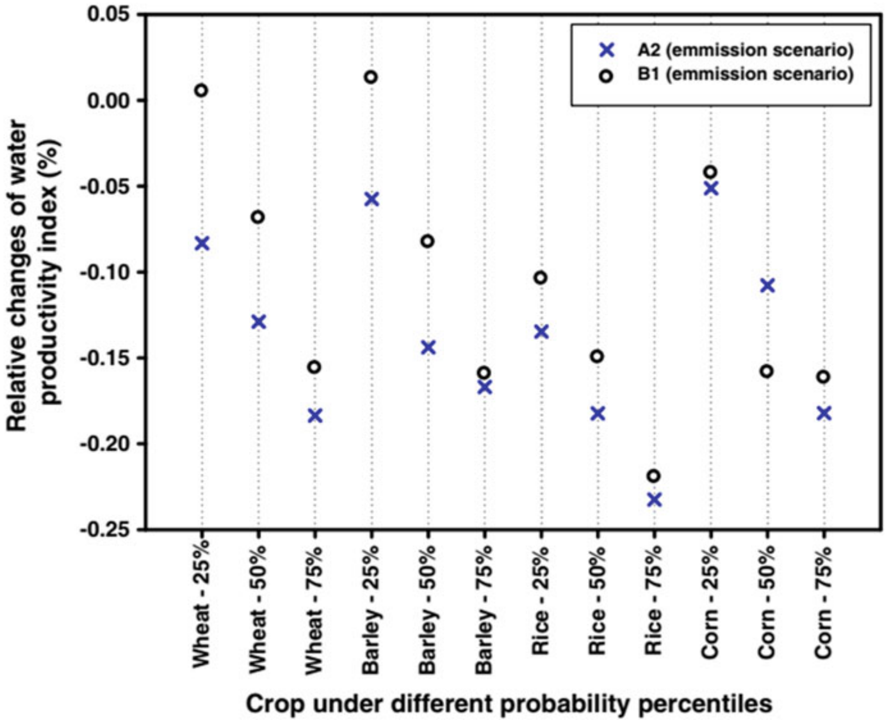

Fig. 1.14 Relative change of the water productivity index under different emission scenarios and probability percentiles until 2044 (Source: Goharia et al. 2013)

Zayandeh Rud Valley from the late Tertiary to Quaternary. They examined the spatial structure of a representative area of the valley in three dimensions, determined responsible geological and geomorphic processes of landscape formation and investigated inherited records and evidences of changes in soil development. During the last century, intensified drought resulted in a vigorous driving force to desertify the eastern part of the basin. This aggressive process is now the most important degradation factor in this valley.

Bateni (2013) shows with a remote sensing analysis in the basin, that between 1997 and 2008, bare lands increased from 5.8% to 20%, while rangelands decreased from 70% to 55%. The results of this study also revealed that degradation of rangeland leads indirectly to the degradation of water quality. Regarding the water quality, in Chap. 9 of this volume Chamani and Karimian show how the Zayandeh Rud River has been subjected to an extensive discharge of wastewater and effluents from several points and nonpoint pollution sources. They studied the sediment quality of the river. A significant rise was observed in the level of river pollutants and ecological risk downstream of Isfahan City, especially after the wastewater treatment plant where any water withdrawal for agricultural and livestock purposes significantly elevates the risk of food-chain contamination with heavy metals. From a methodological point of view, Chamani and Karimian's work underscores the usefulness of chemical pollution indices in representing the spatial distribution of heavy metals.

Aghasi et al. shed light on the environmental contamination in the vicinity of the almost dried up Gavkhuni wetland in Chap. 10 of this book, using the kriging method. The main objectives were to investigate the spatial distribution of soil properties, determine the spatial variations of heavy metals deposition rates in samples collected from the vicinity of the Gavkhuni wetland, and compare heavy metal concentrations among atmospheric dusts, Gavkhuni wetland sediments, and soil surface in the study area. They also asked whether the annual dusts produced in the area were affected by the dry sediments of the Gavkhuni wetland.

The chapters presented above provide a solid overview of environmental and water-related issues in the Zayandeh Rud catchment. It is obvious that from the Zayandeh Rud dam to the lower reaches where the Gavkhuni wetland is located, the situation is becoming more precarious, and that the agricultural sector—as the biggest water consumer—requires particular attention.

1.4.2 Adaptation Strategies for the Zayandeh Rud Catchment

The Zayandeh Rud basin has been and will continue to be facing the impacts of water resources overexploitation, poor land and water management, and climatic change. Emerging conflicts between and within water using sectors as well as increasing pollution of water bodies make firm responses in the region necessary. In this regard, comprehensive evaluation of water resources using virtually reliable methods at appropriate spatial and temporal scales may lead to a sound understanding of water and land resources and their ecosystems and an optimal management of the watersheds. Scientific results of climate change impacts on the Zayandeh Rud basin's climate variables can provide the basis for such appropriate management strategies (Zareian et al. 2016; Eslamian et al. 2017). In the past years, challenges causing water stress with declining surface and groundwater resources and higher water demand have already led to several adaptation strategies at different management levels in the basin (Hoogesteger 2005; Mohajeri and Horlemann 2017; Ebrahimnia and Bibalan 2017; Torfe et al. 2017).

However, the complexity of social and hydrological macro–micro interactions has made a successful governmentally owned and driven adaptation process of water management difficult. In Chap. 2, Mohajeri shows how sublime theoretical management approaches for Iran's water resources have been jeopardized by impractical policies. Sustainability is a buzzword in many political documents but falls short of expectations.

Multilevel governance patterns, which allow interest groups to participate in the sharing of water by forms of cross-scaled co-management, are required in the Zayandeh Rud (Molle et al. 2009). Integrated Water Resources Management (IWRM) is an approach for facilitating a trans- and inter-sectoral sound response towards water management issues. The need for such an integrated approach as well as characteristics, challenges, and success of its application in the Zayandeh Rud Basin are discussed in Horlemann et al. (2018) and Mohajeri and Horlemann (2017). Chap. 11 provided by Grundmann et al. presents the results of two consecutive, interactive workshops carried out in 2016 (with farmers and their representatives) and 2017 (with farmers, representatives, academia, and administration) in the framework of the IWRM Zayandeh Rud project, financed by the German Federal Ministry of Education and Research. The recommendations acquired in these workshops build the foundation for a strategy for agricultural transformation in the catchment. The chapter also presents the participatory methods (citizens' juries, SWOT and TOWS, SPA) used in the workshops and shows how these were adapted to local conditions.

To highlight the need and current state of play, particularly in the downstream region of the basin, Nishikawa provides a case study that focuses on Varzaneh in Chap. 14, the most easterly city of the Zayandeh Rud basin. Based on the results of semi-structured interviews and life-history interviews in Varzaneh, the author describes and illustrates the inhabitants' responses to the environmental changes in an ecological short history from the 1960s. Following the transformation of the diachronic subsistence activities enabled her to examine the lower basin of Zayandeh Rud in relation to the historical background in Iran and the structure of its society.

Environmental education is the core when it comes to implementing sustainable water management throughout the country. In Chap. 12, Azimpour presents the work of the environmental NGO "Women's Society Against Environmental Pollution" on raising environmental awareness and involving citizens in environmental protection projects in the Zayandeh Rud catchment. People from different social classes participate in the NGO's activities. The NGO's activities include holding social responsibility and participation workshops, empowering women in Isfahan's eastern rural areas, helping to form local NGOs or developing alternative revenue. Currently, the government does not support NGOs much, although the support has increased in the past decade. In some activities, especially programs at national level or obtaining permissions, NGOs need more support.

On the more technical side of adaptive action, a system dynamics model by Gohari et al. (2017) suggests that infrastructural improvements, ecosystem-based regulatory prioritization, and water demand management (e.g., replacing high water demand crops) complemented by supply augmentation, may temporarily alleviate water stress in a basin. The reduction of cropped land and change of cropping patterns are found to be vital strategies in securing yields and reducing the water demands of the agricultural sector in the basin (Massahbavani and Morid 2005).

In order to be able to adjust agricultural activities to increasingly difficult climatic conditions, it is necessary to determine the net water requirement of crops. Salemi et al. (Chap. 15 of this volume) calculate the water demand of autumn and spring plants in the eastern region of the Zayandeh Rud river basin. To do so, the reference evapotranspiration (ETo) was calculated using FAO Penman–Monteith equation via coding in visual basic (climate sub-model) and zoning using Arc GIS. By establishing the relationship between the landscape units and the climatic parameters of each synoptic and climatologic meteorological station, ETo amount was measured in rasterized Agricultural Climatically Zone map units. The optimization of computer algorithms and the establishment of a sound database of net water requirements and related maps can help in developing sustainable agricultural sector strategies. Ziaei (Chap. 4 of this volume) elaborates further on the adaptation strategy to reducing farming in the lower reaches of the catchment but also discusses the potentials for greenhouse farming.

In Chap. 16 of this volume, Torabi and Salemi present their ideas on increasing water productivity in the Roodasht area by replacing abiotic stresses with tolerant forages. In the Roodasht region, farming, forage production, animal husbandry, and dairy production are important for meeting nutritional needs. In a time without water restrictions, alfalfa and corn silage have been the main suppliers of livestock forage, but due to high water demand and an inability to use unconventional water (gray water) their production has been severely restricted. In their study, water productivity of sorghum was investigated in a field experiment. The results showed that sustainable production of forage for livestock could be obtained by cultivating sorghum due to its tolerance to abiotic stresses, deep and extant root systems, waxy cover on stem and leaf, as well as the ability to maximize water use efficiency through leaf arrangement and stomatal regulation.

As a functional compilation of adaptive land and water management measures on a local scale, Raber and Reyhani present an Action Plan for the Roodasht region to cope with climate change in Chap. 13 of this volume. Findings of the vulnerability analysis carried out in the project "Feasible Adaptation Strategies for a Sustainable Land Use in the Lower Reaches of the Zayandeh Rud River" (Raber et al. 2018) have been used as the basis for compiling the strategic action plan. The Harvard Negotiation Project approach was used to define and compile adoption measures in a trans- and interdisciplinary participatory process with experts and stakeholders. These defined measures were enriched with international expertise and bundled into sets of concrete measures for reconciling water distribution at basin level, agricultural development, regional management, and the protection of the Gavkhuni wetland. Together, the compiled roadmap is supposed to reduce the vulnerability and strengthen the adaptive capacity of the lower reaches of the Zayandeh Rud towards climatic and socioeconomic change.

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Part I
Water and Land Use Challenges in Iran

Chapter 2
Water Resources and Water Security in the MENA Region

Lars Ribbe and Sudeh Dehnavi

Contents

2.1 Introduction

The MENA (Middle East and North Africa) region, with currently around 500 million inhabitants, is demographically, economically, and politically one of the most dynamic regions in the world. As the region is characterized by severe and growing water scarcity, the issue of water security and sustainable management of water resources is of outstanding relevance, both for current development and for future prospects.

While *water security* does not have a single valid definition, the term usually refers to the available water supply of adequate quality for human or natural demands at the place and time needed as well as to the resilience to water-related natural hazards. The Fig. 2.1 visualizes the four dimensions of water security as well as the relevant framework conditions according to the United Nations (2013).

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Fig. 2.1 The four dimensions of water security and the relevant framework conditions (UN 2013)

The definition of water security refers to a holistic understanding of water availability and demand, considering all types of water needs and issues, recognizing that there is only one single water resource changing its form, place, and time of occurrence through the naturally and human impacted water cycle. While it is beyond the aim and possibilities of this chapter to comprehensively assess water security in the MENA region, this chapter provides some key aspects regarding the special situation of the MENA region and provides an overview of water issues in the wider MENA region. It should be noted that the countries defined as belonging to the MENA region may differ; for example, the UN refers to different countries belonging to Northern Africa (UNDESA 2019) than the World Bank (World Bank 2018).

Globally, levels of water security differ significantly, with the MENA region facing tremendous challenges with regard to per capita water availability,

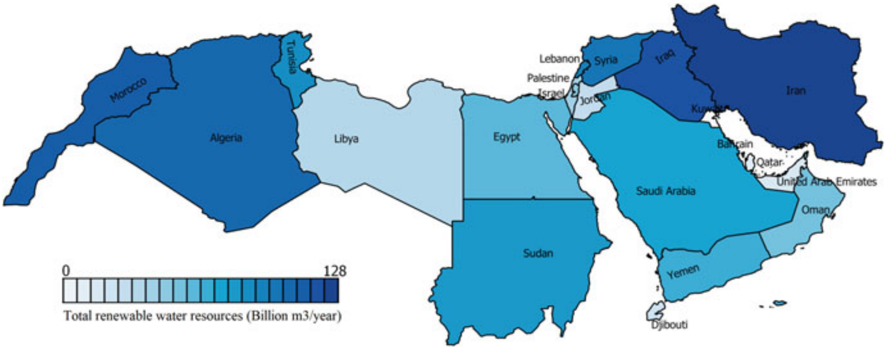

Fig. 2.2 Map of the MENA region indicating total renewable water resources per country in 2014 (10^9 m^3/year) (based on data from FAO Aquastat, 2019)

groundwater depletion, soil and ecosystem degradation and vulnerability to climate extremes. It can probably be considered the least water-secure region, particularly when considering growing pressures deriving from demographic trends and climate change. Figure 2.2 illustrates total renewable water resources in the MENA region countries.

The following two chapters elaborate on key water challenges in the region as well as socioeconomic drivers and implications of water insecurity in the region.

2.2 Key Water Security Issues in the MENA Region

2.2.1 Overuse of Available Water Resources

Water stress describes the ratio of total water abstractions to the available (renewable) water resources. Sustainable Development Goal (SDG) indicator 6.4.2 provides a metric for this ratio. The preliminary quantification of the baseline for the years 2000–2015 is shown in Fig. 2.3.

On the water use side, this indicator includes the water demands of all major sectors. For water availability, it includes renewable surface and groundwater generated within the country and secured inflow from transboundary sources. The method considers environmental flow requirements but the details of this calculation are still being elaborated in most countries. As the special report "Progress on level of water stress—global baseline for SDG indicator 6.4.2" of FAO (2018) highlighted, weak databases in most countries prevent the establishment a reliable set of indicators. Thus, increased efforts in monitoring are required.

However, even with the preliminary dataset shown in Fig. 2.3, it becomes very clear that the MENA region is the most water-stressed region worldwide with most of the countries currently using more than 70% of their available renewable water resources.

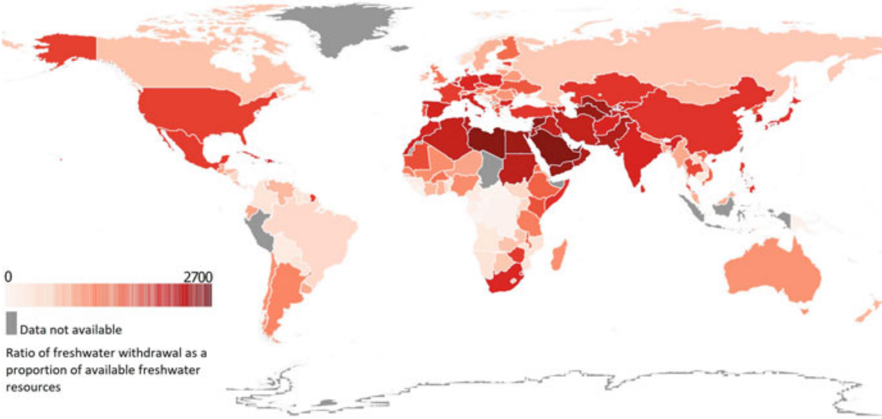

Fig. 2.3 Levels of water stress by country (2014) (based on data from FAO Aquastat, 2019)

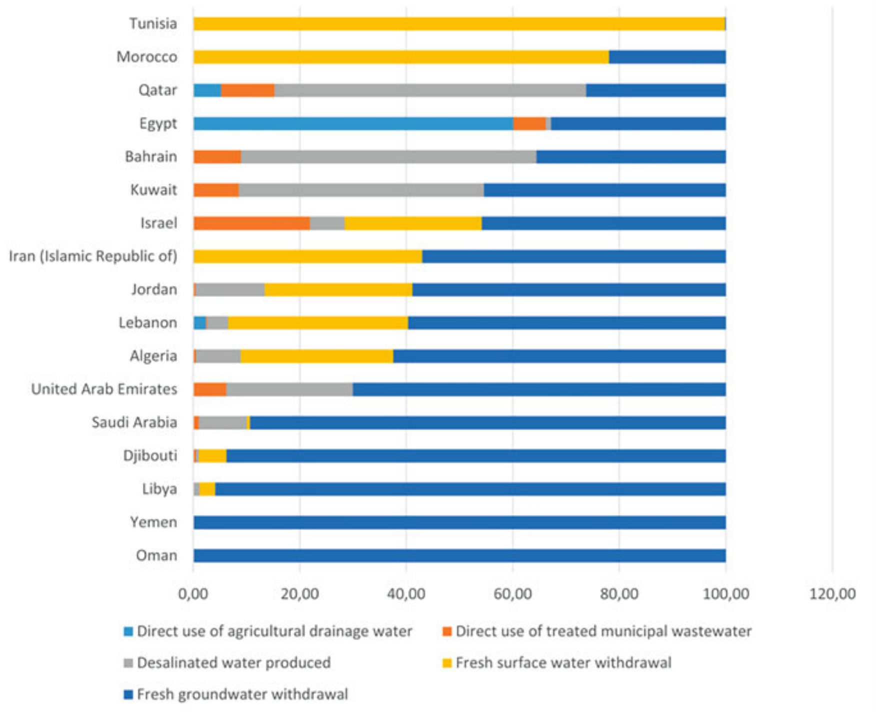

Fig. 2.4 Source of water withdrawals as percentage of total withdrawals (10^9 m^3/year) (FAO 2019)

Figure 2.4 illustrates the sources of water withdrawals as a percentage of total withdrawals according to the country. Special attention should be payed to groundwater withdrawals. As most of the MENA region belongs to the semiarid or arid climate zone, groundwater recharge is quite low, while for most countries and most of the year, groundwater is the only reliable freshwater source. The effects of these withdrawals are the depletion of (nonrenewable) aquifers, which are visible as the drop of water levels (source) or the destruction of groundwater-dependent ecosystems.

2.2.2 *Desalination*

Nonconventional water resources stemming from desalination or direct use of treated wastewater are not included in the statistics on water stress metrics of SDG indicator 6.4.2. In the MENA region, many countries satisfy their water demand by seawater desalination.

Figure 2.5 shows the global distribution of large desalination plants. According to Jones et al. (2019), there are 4826 desalination plants in the MENA region with a combined capacity of $45.3 \times 10^6\ m^3\ day^{-1}$, accounting for 47.5% of the global capacity and contributing to $99.4 \times 10^6\ m^3\ day^{-1}$ (70.3%) of global brine production. For some countries, desalination is the most significant source of water and it is indispensable in guaranteeing water security. However, desalination is related to high energy demands which translate to high greenhouse gas emissions unless the energy sources shift from fossil to renewable. Furthermore, desalination is

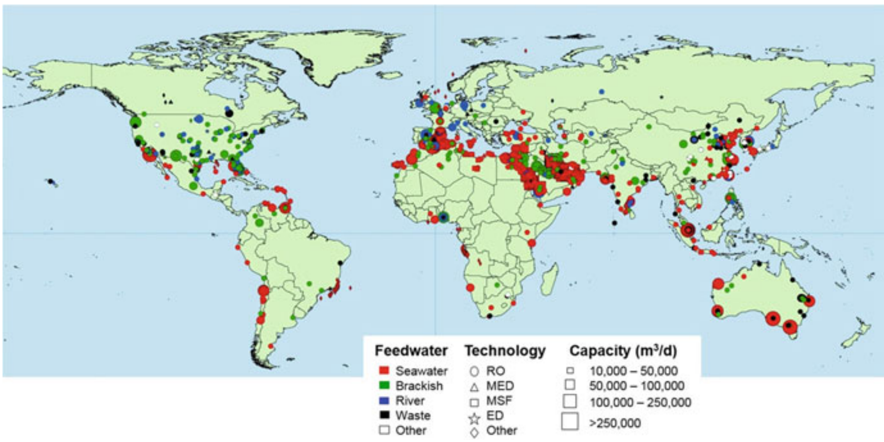

Fig. 2.5 Global distribution of desalination capacities (Jonas et al. 2019) [Reprinted from Science of The Total Environment, 657, Jones, Edward & Qadir, Manzoor & van Vliet, Michelle & Smakhtin, Vladimir & Kang, Seong-mu., The state of desalination and brine production: A global outlook. Science of The Total Environment., 1351., Copyright (2019), with permission from Elsevier [Science of The Total Environment]]

associated with strong environmental impacts on sensitive terrestrial and coastal ecosystems if brines are not treated and disposed of in an adequate way.

2.2.3 Wastewater Treatment and Reuse

In the MENA region, access to drinking water and sanitation coverage is similar to global averages, with some countries having close to 100% coverage and a few less than 70% (Palestine, Sudan, Djibouti, and Yemen); see Fig. 2.6.

The proportion of wastewater that is safely treated is low for most countries compared to the world average (compare Fig. 2.7). Adequate treatment is a

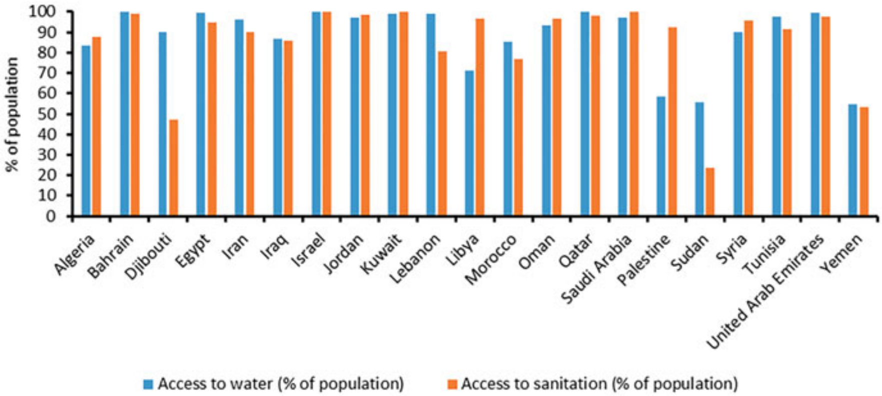

Fig. 2.6 Access to improved water and sanitation (FAO 2019)

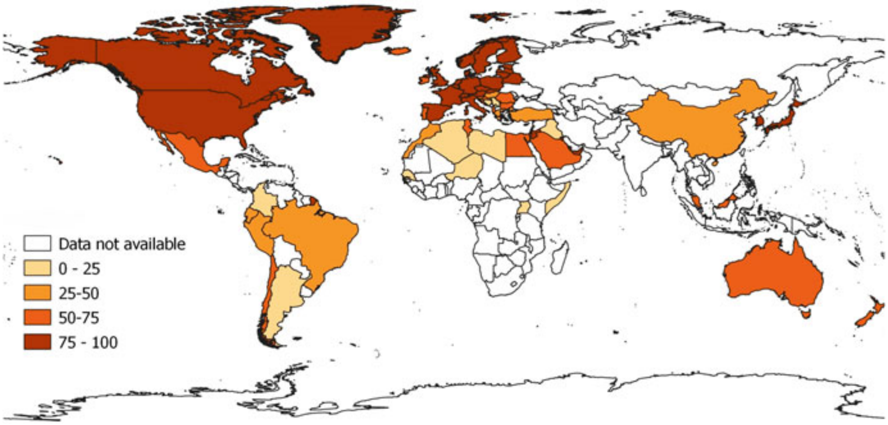

Fig. 2.7 Global status of Indicator 6.3.1 Proportion of wastewater safely treated (%), from households (based on Data from WHO and UN Habitat 2018)

prerequisite for the risk-free reuse of wastewater, meaning that the potential of using treated wastewater as a nonconventional source of water is not currently fully exploited. This is particularly important as total (municipal and industrial) wastewater production is continuously increasing (as demonstrated by the global national statistics provided through Aquastat—FAO 2019).

2.2.4 Water Use Efficiency and Water Losses

In water-scarce regions, increasing water use efficiency and reducing losses are highly relevant to help to close the water gap or to account for growing future demands. Irrigated water use efficiency differs widely in the MENA region and is difficult to measure. SDG indicator 6.4.1 aims to monitor the trend of economic output compared to water abstractions of water-intensive sectors. So far, no reliable information is available for the MENA countries. Regarding physical water losses from the domestic sector, the Arab League estimates that on average physical losses in the urban water system are around 20% (Arab League 2015), which amounts to an estimated total of almost 6×10^9 m^3 $year^{-1}$, thus emphasizing the huge "hidden resource" in preventing these losses.

2.2.5 Available Water Resources and Climate Change

While the abovementioned key issues highlight the relevance of growing demands or low efficiencies and system losses as a problem for the demand side, there is also growing concerned that water supply levels will decrease in the future. On the one hand, this is due to increasing abstractions in upper riparian countries or overexploitation of groundwater, on the other hand, further water stress is likely to be induced by decreasing precipitation in combination with increasing temperatures, with impacts on surface runoff and groundwater recharge. The Mediterranean is one region where the various Global Circulation Models unanimously predict a downward trend in future precipitation. Even more certain, the temperature is very likely to increase with the consequence of higher irrigation demands and higher evapotranspiration, leaving less water in the system for runoff and recharge. Consequently, based on the annual mean hydrological cycle change for runoff presented by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Working Group I (IPCC 2013, p45), it can be concluded that the MENA region is impacted particularly hard leading most likely to significant decrease of runoff in the MENA region in the decades to come.

Table 2.1 Population, GDP, and GNI in the MENA region and worldwide

	Population (million inhabitants)	GDP (current 10^9 US$)	GDP per capita (current US$)	GNI per capita[a] (current US$)
MENA region	465 (6.19% of world population)	3315.37 (4.10% of global GDP)	7128.53 (66% of global average)	6955.61 (66% of global average)

Source: World Bank national accounts data and OECD National Accounts data files (2017)
[a]Atlas method

2.2.6 Socio-Economics of MENA Region and Water Security

This section presents different sets of data and information to provide an overall picture of the social and economic situation in the MENA region, its impact on water security, and vice versa. It uses the Gross Domestic Product (GDP) of the MENA countries, which is the most common indicator used for the ranking of countries based on their economic development (Milenkovic et al. 2014). The Gross National Income (GNI) and GINI index are also used in this chapter to demonstrate, respectively, the living standards and the deviations of income distribution among individuals or households within an economy from a perfectly equal distribution. Other indicators compared in this section are population, water productivity, and unemployment, and migration trends in the region.

Population increase and economic growth are among the main triggers of growing water demand and use. Table 2.1 lists the population, GDP, and GNI related data for 2017 for the countries of the MENA region.

A comparison of the GDP per capita in the MENA region to the worldwide numbers indicates moderate economic development of the MENA region. However, high variation is observed among the countries of the MENA region (Table 2.2). Countries with different economic status and wealth follow different strategies to foster economic growth and to cope with increasing water demand and scarcity.

According to Dadson et al. (2017), countries with challenging hydrological conditions that aim for sustainable growth require a significant fraction of national wealth for investment in infrastructure and institutions to increase the water productivity and to reduce water-related risks. If those countries lack wealth, they are most likely to descend into a poverty trap. A lack of available resources to invest in infrastructure and institutions can lead to unsustainable development strategies that exacerbate water scarcity. Conversely, water scarcity can impose constraints on production and economic growth (Sachs et al. 2004). Whittington et al. (2013) identified reliable supply of water as a production factor crucial for the development of many sectors of an economy, especially agriculture and energy.

Sun et al. (2019) discuss the link between economic growth and water demand is nonlinear. Their study reveals that in many regions in China, population growth and economic development initially led to higher water demand and eco-environmental degradation due to earlier water overexploitation. Further water demand pressures

Table 2.2 Main economic indicators of the MENA countries with respect to the averages of the MENA region

	Population (% of total)	GDP (% of total)	GDP growth	Ratio of GDP per capita to average of region	Ratio of GNI per capita[a] to average of region	GINI index[b]
Saudi Arabia	7.12	20.77	−0.74	2.92	2.87	NA
Iran, Islamic Rep.	17.35	13.69	3.76	0.79	0.79	40
United Arab Emirates	2.04	11.54	0.79	5.66	5.57	NA
Israel	1.87	10.66	3.44	5.69	5.38	38.9
Egypt, Arab Rep.	20.74	7.10	4.18	0.34	0.44	31.8
Iraq	8.07	5.83	−1.67	0.72	0.69	29.5
Algeria	8.90	5.05	1.60	0.57	0.57	27.6
Qatar	0.59	5.03	1.58	8.59	8.43	NA
Sudan	8.78	3.71	4.28	0.42	0.34	35.4
Kuwait	0.87	3.61	−3.48	4.13	4.57	NA
Morocco	7.77	3.31	4.09	0.43	0.41	39.5
Oman	1.00	2.14	−0.93	2.13	2.08	NA
Lebanon	1.46	1.61	0.55	1.10	1.08	31.8
Jordan	2.10	1.23	2.12	0.58	0.58	33.7
Tunisia	2.46	1.21	1.82	0.49	0.51	32.8
Libya	1.41	1.15	26.68	0.81	0.77	NA
Bahrain	0.32	1.07	3.80	3.33	3.05	NA
Yemen, Rep.	5.98	0.81	−5.94	0.14	0.15	36.7
West Bank and Gaza	0.96	0.44	3.14	0.46	0.51	33.7
Djibouti	0.20	0.06	4.09	0.27	0.29	41.6
Syrian Arab Republic[c]	NA	NA	NA	NA	NA	35.8

Source: World Bank national accounts data, and OECD National Accounts data files (2017)
[a]Atlas method
[b]World Bank estimate
[c]No data was available for Syrian Arab Republic

led to industrial structure upgrades, water use efficiency improvement and water conservation to reverse the increasing trend of water use. However, some countries from the MENA region with good economic status experience an increasing level of water use. This is despite large investments in nonconventional sources of water

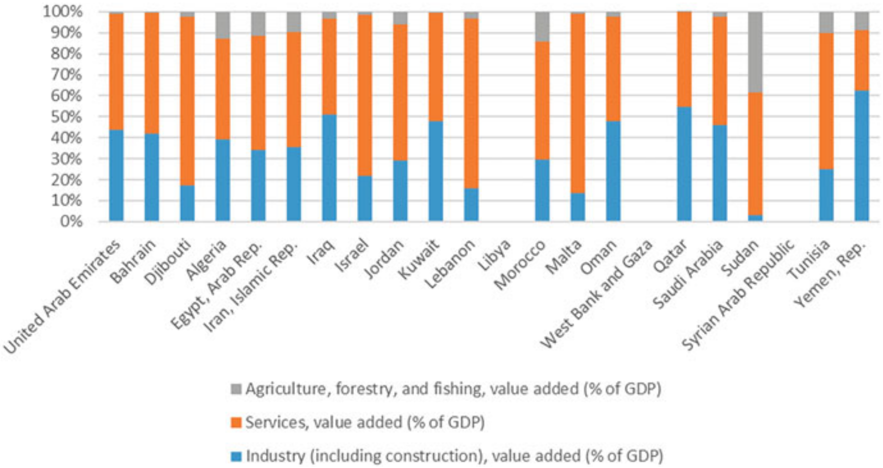

Fig. 2.8 Value added of different sectors as a percentage of total GDP in 2017 (FAO, AQUASTAT data)

supply such as desalination and new technologies for wastewater treatment plants to cope with water scarcity. For example, Qatar has experienced continued increases in GDP; total GDP (constant 2010 US$) in 2016 was about 2.1 times higher than in 2007 (an increase from 79.4 million US$ to 170.7 million US$). In the same period, total water withdrawal and population increased by the same rate (from 0.437 million cubic meters to 0.912 million cubic meters; from 1.2 million inhabitants to 2.6 million inhabitants).

In Qatar, the highly subsidized produced water eradicates any incentive to reduce demand. Quality of life, lifestyle, and climate conditions are among the main drives of higher water use. Moreover, the religious, social, and cultural preferences restrict the reuse of the treated wastewater. However, as long as the environmental externalities of such technologies are neglected, especially on marine ecosystems, the reduced water scarcity will not comply with the definition of water security.

About 20.77% of the total GDP of the selected countries was observed in Saudi Arabia, which accounts for only 7.12% of the total population of the MENA region. This is followed by Iran and the United Arab Emirates with 13.69% and 11.54%, respectively. Djibouti, with 0.2% of the total population, had the lowest share of GDP (0.06%) among the selected countries. Most of the countries showed a positive GDP annual growth rate in 2017. Libya experienced the highest annual growth rate of 26.68% in 2017. Yemen, Kuwait, Iraq, and Saudi Arabia had negative growth rates compared to 2016.

Figure 2.8 demonstrates the value added of different sectors to the economies of the selected countries as a percentage of GDP. In all selected countries, the share of the agriculture sector from GDP is less than 13%, except Sudan with about 30%. In all the countries except Iraq and Yemen, the service sector has the highest contribution to GDP.

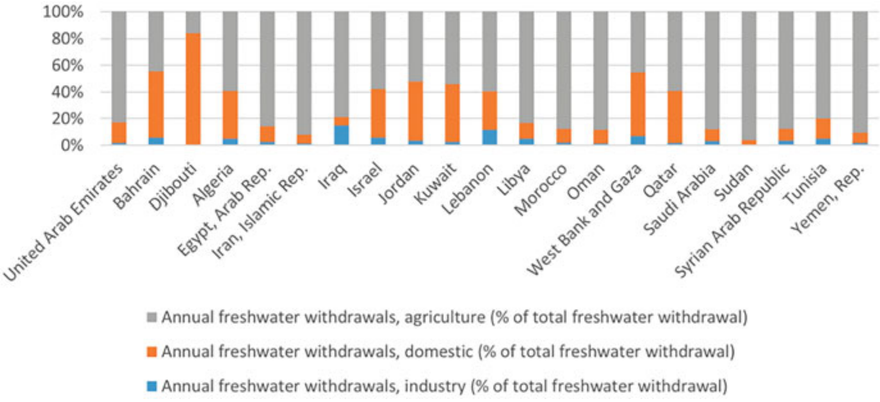

Fig. 2.9 Annual freshwater withdrawals for different water uses in MENA region (FAO, AQUASTAT data)

In contrary to the low contribution of the agriculture sector to the GDP, the highest share of freshwater withdrawals is allocated for agricultural purposes in all the selected countries except Bahrain, Djibouti, and West Bank (Fig. 2.9). Sudan, Iran, and Yemen allocate 96%, 92%, and 91% of freshwater withdrawals to their agriculture sectors, respectively.

These data could be interpreted to show that in the MENA region, large quantities of water are used in the agricultural sector with low contributions to the GDP. Table 2.3 presents the shares of water allocated for each sector to the percentage of the GDP produced by that sector. The ratio of GDP generated by industry to the total GDP in Oman is 34 times higher than the ratio of water withdrawal allocated for that sector to total water withdrawal. Numbers higher than 1 indicate the positive efficiency of water allocation in that sector concerning GDP.

Table 2.3 indicates low contribution of freshwater withdrawals to GDP in agriculture compared to industry in all the MENA region countries. These data could be interpreted to demonstrate that the economic efficiency of the used water is not a key factor in decision making for freshwater allocation. In fact, water allocation is rather a political decision. For example, in Iran, food security and independency in the production of strategic crops is a political decision that outweighs water security without considering water economic value and allocation efficiency (Dehnavi 2015). This decision has caused a conflict between food security and water security in long-term outlook. Considering water as an economic good in decision making for water use and allocation could support efficient water use and allocation. A strong and stable regional market reflecting the comparative advantages of the member countries and virtual water flows could enhance trade among the MENA countries towards water security.

The Gross National Income (GNI) measures living standards. Qatar has the highest rate of GNI per capita in the MENA region, followed by Israel and the United Arab Emirates. Yemen had the lowest GNI per capita, about 55 times less

Table 2.3 Ratio of the water allocated for each sector from total withdrawal to the share of GDP produced by that sector (calculated based on Food and Agriculture Organization and World Bank data)

Country Name[a]	United Arab Emirates	Bahrain	Algeria	Egypt, Arab Rep.	Iran, Islamic Rep.	Iraq	Israel	Jordan	Kuwait	Lebanon	Morocco	Oman	Qatar	Saudi Arabia	Sudan	Tunisia	Yemen, Rep.
Industry	25	7	8	13	30	3	3	8	24	1	13	34	32	15	8	5	23
Agriculture	0.01	0.01	0.21	0.13	0.10	0.04	0.02	0.11	0.01	0.05	0.14	0.03	0.00	0.03	0.32	0.12	0.07

Source: based on FAO, AQUASTAT data

[a]No data was available for Libya, West Bank, Syrian Arab Republic, and Djibouti

than Qatar. A GINI index of 0 represents perfect equality, while an index of 100 implies perfect inequality. Though the GNI per capita in Iraq is less than the average of the region, the GINI index (29.5%) shows a higher level of equality compared to the other countries.

Looking at the impact of water scarcity on economic growth, little evidence indicates significant impact of water scarcity on slowing the long-term rate of national economic growth. Still, looking at the local scale, this effect can have a devastating impact on energy, crop production, and unemployment (Hertel and Liu 2016).

2.2.7 *Labor Market, Unemployment, and Migration*

In total, 4.7% of the total labor force worldwide is located in the MENA region. About 9.5% of the labor force in the region is unemployed, a number that is 1.9 times higher than the global average. The unemployment rate among the MENA region countries varies between 0.14% in Qatar and 30% in West Bank and Gaza. Figure 2.10 demonstrates the share of employed and unemployed labor force in the MENA region. Creating new job opportunities to reduce unemployment rates and increase the welfare of the population has been of high importance in the MENA

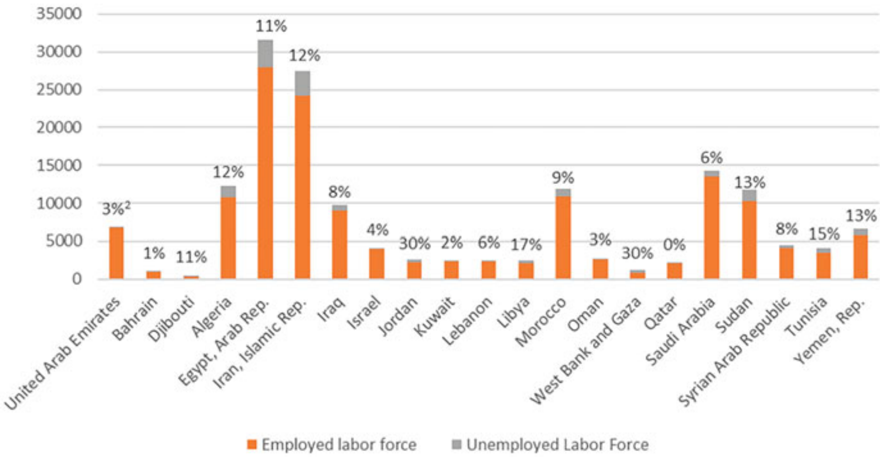

Fig. 2.10 Number of employed and unemployed labor force (1000 persons) in countries of MENA region in 2018 (World Development Indicators 2019) (1) Labor force comprises people ages 15 and older who supply labor for the production of goods and services during a specified period. It includes people who are currently employed and people who are unemployed but seeking work as well as first-time job seekers; however, not everyone who works is included. Unpaid workers, family workers, and students are often omitted and some countries do not count members of the armed forces. Labor force size tends to vary during the year as seasonal workers enter and leave (World Bank database). (2) Labels indicated percent of unemployed labor force

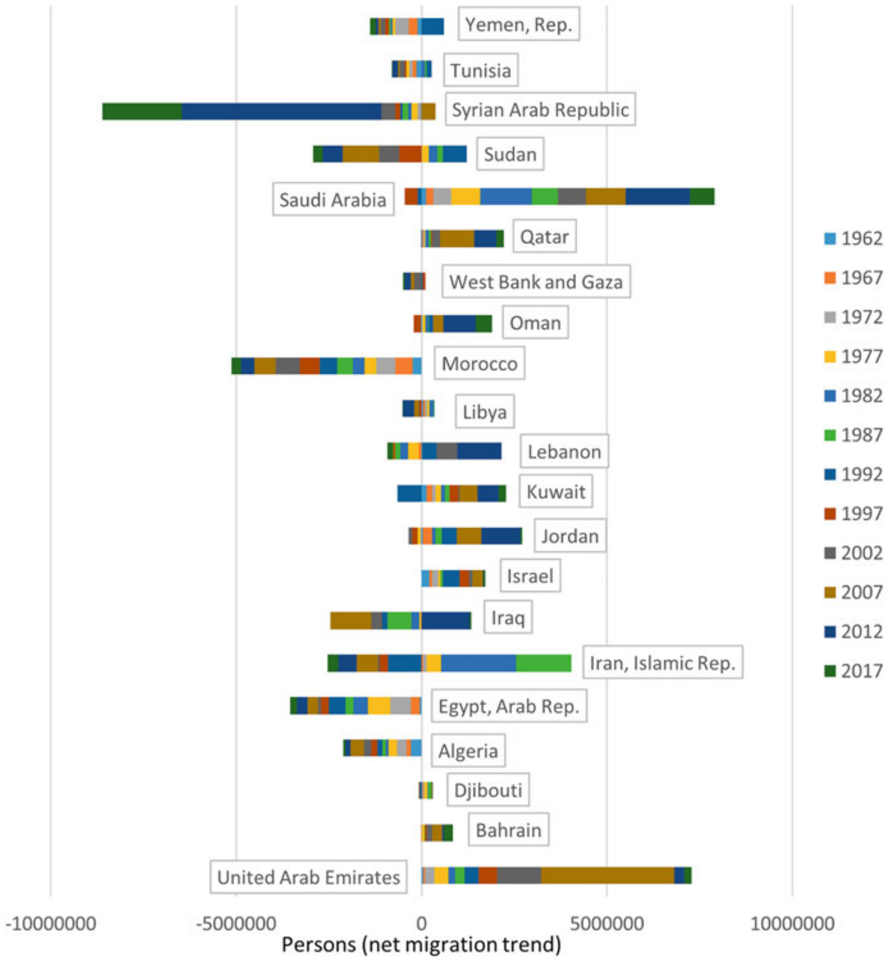

Fig. 2.11 Net Migration Trend between 1962 and 2017 in the MENA region (World Development Indicators 2019) Net migration is the net total of migrants during the period, i.e., the total number of immigrants less the annual number of emigrants, including both citizens and noncitizens. Data is 5-year estimates

region. However, the relevant policies and strategies at the sectoral level should consider the implications of their decisions and actions on water use.

36% of the labor force in the MENA region is from Egypt and Iran, with an average of 11.7% unemployment rate. Considering the total unemployed labor force in the region, 42% are from Egypt and Iran. Both countries experience low levels of water security and any sustainable decisions and actions in creating new jobs—especially in agriculture-related sectors—should consider the water efficiency and productivity principles. Unemployment and worsening economic status have been influencing factors that have led to migration from and to MENA region countries.

Migration is a risk factor for any water security planning in the region. Figure 2.11 shows net emigration and net immigration countries in the region. The diverse economic development status of the MENA countries, political instability, and conflicts in the region have triggered displacement within the region. For example, about one-fourth of the population in Lebanon are immigrants, mainly from Syria. Syria has, especially between 2012 and 2017, the highest rate of emigration due to the Syrian war. Most of the migrants settled in neighboring countries including Turkey, Lebanon, and Jordan.

In the MENA region, which is the most water-scarce global region, any actions that cause displacement of the population can critically affect water security in both countries of origin and destination. Migration and human displacement may reduce pressure on water resources of the region of origin and offer new opportunities to the migrants. However, distressed migration could lead to an increase in water demand at the regions of destination and can create social, economic, and environmental challenges at different scales. Water scarcity has already had significant impacts on internal migration and therefore water security at the national level. The migrants typically have low economic status and are the most vulnerable to water scarcity and its social and economic consequences. They can mostly afford to move to the next village or city with better conditions. In Iran, water scarcity has already resulted in the migration of former farmers to nearby villages and cities as well as to the capital (Dehnavi 2015). A continuation of the existing social, economic, and political trends could expand its effects at the international level as well.

2.3 Conclusion and Outlook

The MENA region is probably the most water-stressed part of the world. In addition, estimates on population growth suggest a strong increase in the region from today, suggesting increases of around 500 million to more or less 1 billion inhabitants by 2100 (UNDESA 2019). Even if parts of the future food demands could be met through raising food imports, increased municipal, irrigation, and industrial water demands will be noticeable in the future. These challenges and the growing water insecurities must be counteracted by boosting water use efficiency, the use of nonconventional water sources such as desalination and reuse of wastewater, and reducing demand, improving monitoring of the whole water cycle as well as changing water allocation and water productivity. To address these challenges, tremendous and coordinated efforts need to be made to reach technological and social innovation in this direction.

Many solutions such as desalination, wastewater reuse, or advanced irrigation techniques require considerable investments. These technologies could contribute to the overall water security, only if the need to mitigate negative environmental consequences like water pollution, greenhouse gas emissions, and deterioration of ecosystems, especially marine ecosystems for the case of desalination is simultaneously achieved. Moreover, these innovations will probably not be sufficient to bridge the gap between supply and demand. Additionally, incentives and awareness raising towards a behavioral change regarding consumption patterns, lifestyle, and social and cultural concerns are needed in order to curb demand.

To increase water efficiency and reduce water losses, the social and economic value of water should be considered. Clear policies and instruments are needed to quantify the social and economic value of water, which is indispensable to foster the adoption of water-efficient technologies as well as building institutional capacities for technology transfer and adoption. Increasing water efficiency requires investment in infrastructure and institutions. Defining water prices at least at its full cost recovery would promote a shift towards more water use efficient technologies and make those investments economically feasible.

To change water allocation towards water security, factors of water productivity and economic value of water at local, national, and regional levels should be a central theme. This demands a change of water allocation to sectors that are more "essential" for water security and some countries means to import virtual water from water-rich parts of the world. Different rules, policies, and framework conditions are required to promote trade of water-intensive goods which allows to compensate regional and temporal water shortages by importing "virtual water" which could substitute domestic water sources.

Finally, yet importantly, peace and stability play a fundamental role in achieving water security. A politically stable MENA region could provide the conditions to attract investments in water innovations and could pave the way for a regional—be it virtual or real—water market that regulates water allocation based on economic, social, and ecologic value and would guarantee a safe supply of water to people, economy, and nature as a pillar for sustainable development.

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Chapter 3
Water Management in Iran: Appearance and Reality

Shahrooz Mohajeri

Contents

3.1 Introduction

The overall water policy of the Islamic Republic of Iran was adopted by the political and religious leader Ali Khamenei on January 22, 2001, and submitted to the state authorities for implementation.[1] The regulation describes the main fields of action for sustainable water management in five points:

1. Development of a holistic management of water resources according to the principles of sustainable development and spatial planning of the country.
2. Increasing efficiency and paying particular attention to the economic and security value of water in terms of supply, use, and protection of this resource.

[1] http://farsi.khamenei.ir/news-content?id=29282. Accessed Feb 2020.

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3. Increase the availability of and protection against anthropogenic and natural pollution of water resources.
4. Creation of a holistic water management plan [...] Increase of scientific capacities and strengthening of the role of the population in water use.
5. Retention of all water resources within national borders.

In order to achieve the goals in the main fields of action, the Ministry of Energy, responsible for water affairs in Iran, defined the following mission statement for its actions as the institution with primary responsibility for integrated and sustainable water resources management:

> For an integrated management of water resources in the country and for the adaptation to climate and environmental conditions in order to create balance and sustainability between water resources and consumption, as well as to provide qualitative and quantitative protections, and to improve the water resources efficiency, the Ministry of Energy will act in such a way in the water sector to ensure that the country excels for all countries in the region in respecting the rights of all stakeholders and equitable access to safe and sufficient water.
>
> This is achieved through the direct involvement of the economic, cultural, social, infrastructure and service sectors within each catchment of the country. (Ministry of Energy 2018: 24, rough translation)

For the implementation of the mission statement, the Ministry of Energy has drawn up 38 strategies, which includes the comprehensive implementation of integrated water resources management, water consumption management, groundwater rehabilitation, a reorganization, and decentralization of decision-making structures up to cost-covering water prices and which, in the opinion of the author of this chapter, could enable sustainable, integrated, and future-oriented water management.

In order to control the implementation of the strategies, three planning instruments have been developed: (1) a long-term Outlook Plan, adopted in 2005, which sets overall policy objectives up to 2025; (2) medium-term national 5-year development plans, which derive and concretize sub-goals from the overall objectives of the Outlook Plan; (3) annual plans with the highest degree of specification.

The promising mission statement with the defined implementation strategies and the structured implementation planning arouse great expectations, but they are hardly visible in the Iranian water management reality.

For example, if one looks at the activity reports of the Ministry of Energy (Ministry of Energy 2018), one quickly realizes that the measures implemented are almost exclusively the development of technical infrastructures. The words ecology, economy, and society are not mentioned once, apart from the first chapter in which Iranian water policy and the mission statement of the ministry are reproduced. While the targets were overachieved with the construction of two dams with a total capacity of 2.8 million m^3, the report shows that the targets set for the reduction of nonrevenue water have been scarcely implemented. While 80% of the targets for the construction of hydropower plants with an average annual energy production of 25,700 gigawatts/hour have been achieved, no significant water monitoring facilities have been established (ibid.: 237 ff.). These are just a few examples to show the discrepancy between appearance and reality in Iranian water management.

In order to better understand the immense water management challenges in Iran and the mismatch between "want" and "can," the following section describes and interprets the most important features of the Iranian water sector.

3.2 Outline of the Iranian Water Sector

3.2.1 Iran's Water Management Structure

Iran is characterized by a centralized administrative structure that sets strict guidelines for state action. This is also reflected in the Iranian water sector. Here the Ministry of Energy is the key actor, with its two subordinate units and the steering instruments already mentioned—the long-term Outlook Plan, the medium-term National Development Plan, and short-term annual plans (Mohajeri and Pouriafar 2016: 16).

The Ministry of Energy is responsible for the control and protection of water resources and the infrastructure for water supply and sanitation, in addition to its tasks for electricity generation and supply. Two holding companies for the water sector report to the Ministry:

– Iran Water Resources Management Company (IWRMCo)
– National Water and Waste Water Engineering Company (NWWEC)

These act as national supreme authorities for the fulfilment of the political requirements of the Ministry of Energy in their respective subject areas. They thus act as hinges between the ministry and the operational levels and are responsible for the gradual implementation of the government's planning goals (cf. Mohajeri et al. 2009).

The IWRMCo is responsible for the extraction, management, and transport of surface and groundwater resources with central water management tasks such as:

– Development of strategies and proposals for medium- and long-term water management planning.
– Data collection, analysis, and evaluation.
– Authorization for water abstraction and monitoring.
– Promotion of efficient water use, research and development, education and training, and public relations and participation.

In order to fulfil these tasks, 31 Regional Water Authorities at the provincial level are subordinate to the IWRMCo, whose activities are also monitored by the IWRMCo.

The NWWEC is responsible for the organization, management, and supervision of the entire water supply and sanitation infrastructure. To carry out the operational tasks at hand, NWWEC makes use of the Water and Wastewater Companies which are subordinate to it.

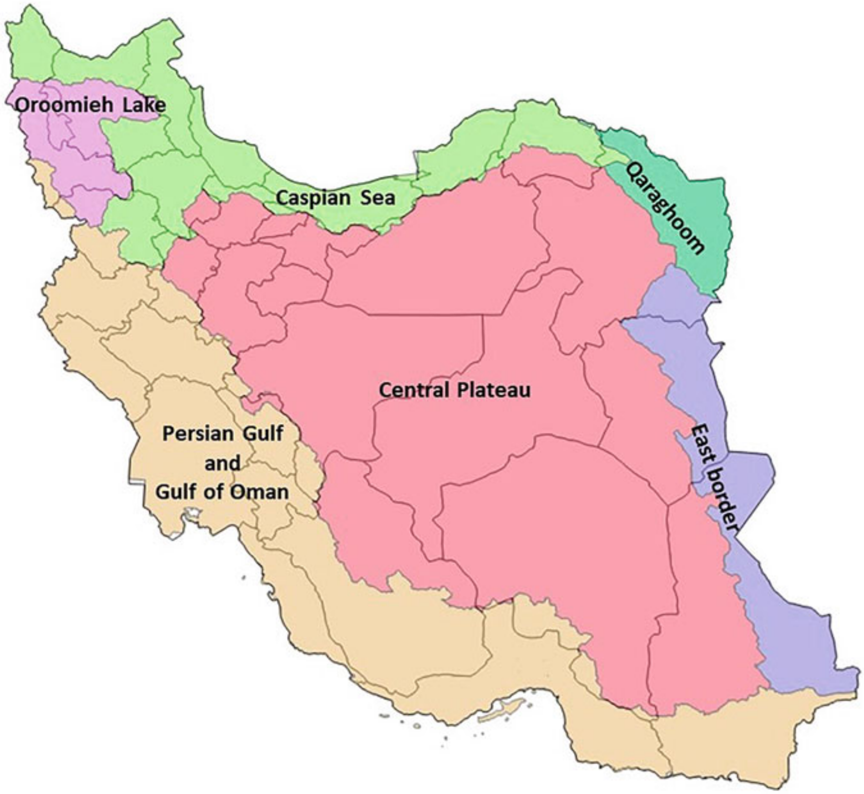

Fig. 3.1 Main catchment areas in Iran, source: by author

The management level of the Ministry of Energy, the subordinate authorities, and companies that develop Iranian water policy and corresponding implementation strategies consist of very well-trained engineers who, however, have little understanding of the socioeconomic issues of water management. The management level and employees of Regional Water Authorities and Water and Wastewater Companies, who are responsible for supply and disposal, are also well-trained engineers with a great affinity for structural solutions.

This technical formation is one of the greatest challenges for the implementation of integrated and sustainable water management in Iran.

3.2.2 Iran's Water Resources

Iran, with a total area of 1.65 million m^2—about 4.6 times the size of Germany—is divided into six main catchment areas or 30 sub-catchment areas (see Fig 3.1, for more information see Mohajeri and Pouriafar 2016: 9ff.). With an average long-term precipitation of 429 mm/a the main catchment area on the Caspian Sea has 3.5 times more precipitation than the eastern catchment area.[2] These clearly different amounts of precipitation require very different management and action decisions, the implementation of which pose particular challenges for decision-makers in a centrally organized country like Iran.

This challenge becomes even greater when taking into account the average long-term precipitation rate has been decreasing steadily. If we look at the average long-term precipitation over the last 50 years, this value is 243 mm. This value decreases by 16% to only 204 mm if one looks at the average long-term precipitation of the last 10 years.[3] At the same time, the temperature has risen by an average of 1.1 °C since the end of the 1990s, with demonstrably negative effects on, among other things, snowmelt or evaporation (Ebrahimnia and Jafari 2017: 14f.).

The runoff volume is also significantly affected by increased temperature. Changes have been noted in the frequency distribution of individual precipitation events in terms of quantity, duration, and intensity. For Iran as a whole, runoff fell by 53% compared with the average long-term runoff volume, although this value has fallen by up to 80% in the East border catchment area (cf. Fig. 3.2) (Ministry of Energy 2018: 43).

If the influence of climate change described above is translated into available renewable water quantities, there is a clear decrease in this quantity from an average of 125 billion m^3/a in the year 2000 to only 89 billion m^3/a by 2015, i.e., around −28% (Ebrahimnia and Jafari 2017: 16). In 2012, 14 of 31 Iranian provinces were experiencing light water stress, eight other provinces in the southeast of the country were experiencing increased water stress and three provinces in the northwest (Ilam, Kermanshah, Lorestan) were already threatened by water shortages (Fig. 3.2).

This decrease of renewable water quantity is contrasted by an increase in population with rising water demand (see Fig. 3.3). For example, since the 1950s the renewable water quantity per inhabitant has fallen continuously from an annual value of around 6800 m^3/inhabitant to around 2000 m^3/inhabitant in the 1990s. In the last decade, this amount has dropped to around 1600 m^3/inhabitant and, according to forecasts by the Ministry of Energy, will reach just under 1100 m^3/inhabitant in 2040 (Ebrahimnia and Jafari 2017: 17).

No statement can be made on water quality and changes in the quality of water resources as a result of, inter alia, changes in precipitation regimes or anthropogenic pollution. There is no publicly available scientific study and statistical data on this.

In summary, it can be said that Iranian decision-makers are clearly facing the challenge of meeting the water needs of water users in a sustainable manner.

[2]In Germany, the average precipitation rate since 1990 is about 792 mm/a. The average precipitation in the German federal states north of the Alps is about 1.5 times higher than in the driest states such as Berlin. See www.dwd.de/DE/leistungen/zeitreihen/zeitreihen.html, last accessed Feb. 2020.

[3]The change in the average long-term precipitation rate varies greatly from region to region in Iran. This value lies, for example, between −27% and −59% for the nine sub-catchment areas of the main catchment area in the Persian Gulf (cf. Ministry of Energy 2018: 35–36).

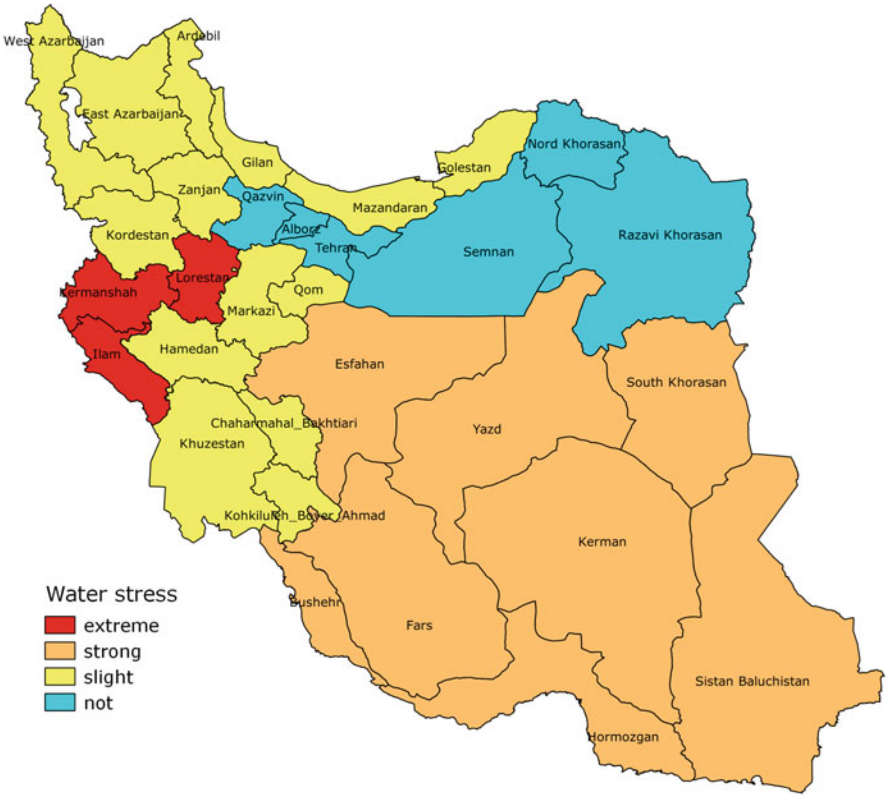

Fig. 3.2 Iranian provinces and the respective characteristics of water stress. Source: By author

However, the intensity of this challenge varies greatly in different regions, for example, depending on the degree of water stress, the extent of land and water use by agriculture or population density.

3.2.3 Rising Water Consumption

The total annual water consumption in Iran has more than doubled over the last 50 years or so, from 44.7 billion m^3 in 1963 to 100 billion m^3 in 2015. The amount of water used per capita has fallen by a third over the same period (see Table 3.1) (Ministry of Energy 2016). Of this total, about 40% is currently covered by surface water and 60% by groundwater.

Agriculture is Iran's largest water-consuming sector by a huge margin, with a share of over 90%. Although this share has fallen by almost 7% in recent decades due to the steadily growing demand from the water supply and sanitation sector and industry, it is still too low. However, the absolute value has more than doubled from

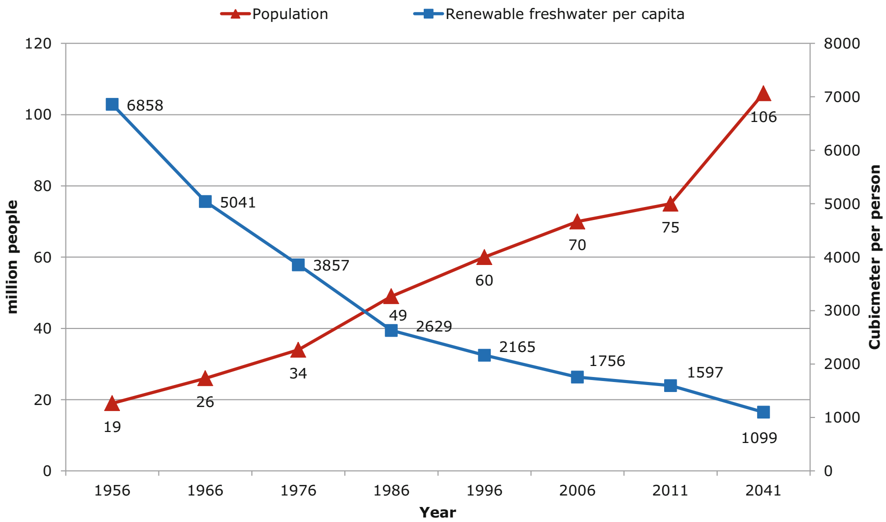

Fig. 3.3 Trend of population increase in and reduction of per capita renewable water in Iran in different years. Source: Ministry of Energy (2016)

Table 3.1 Absolute and relative water consumption by sector since 1963

	1963	1979	1988	1996	2001	2015
Agriculture [bn m^3]	44.1	49.8	70.6	81.4	86.0	92.0
	98.6%	95.6%	94.8%	93.8%	92.4%	0.92
Household [bn m^3]	0.6	1.9	3.2	4.5	6.0	6.5
	1.3%	3.7%	4.3%	5.2%	6.4%	6.5%
Industry [bn m^3]	0.03	0.4	0.7	0.9	1.1	1.5
	0.07%	0.8%	0.9%	1.0%	1.0%	1.5%
Total [bn m^3]	44.7	52.1	74.5	86.8	93.1	100

Source: Ministry of Energy (2016)

44 billion m^3 per year to 92 billion m^3. Table 3.1 compares the absolute and relative water consumption of the three sectors for 6 years.

Forecasts on the long-term development of water consumption show that the amount of water used will remain at a similar level of around 99.6 billion m^3 by 2020 (Global Water Intelligence 2016). No changes in total water consumption are expected until 2030. In terms of sectoral distribution, the existing trend of shifting from agriculture (2020: 87.3%, 2030: 82.7%) towards households (2020: 9.4%, 2030: 12.2%) and industry (2020: 3.3%, 2030: 5.0%) will continue (ibid.).

3.2.4 Iran's Water Economy

Former Iranian Energy Minister Hamid Chitchian sees the growing deficit between revenues and expenditures in the water sector as the most important challenge and the greatest threat to achieving the politically defined water management goals.[4] According to Chitchian, the origin of this challenge lies in the emerging social expectations after the Islamic revolution in 1979, when the view spread quickly that tasks of general interest, such as water or energy supply, should be provided by the state at no cost.

The 8-year Iran–Iraq war 1 year after the revolution, couple by political pressure and lack of expertise in the new administration led to a reduction in water prices, as well as electricity prices.

Only after the war were pricing gradually raised from the 1990s onwards in such a way that the increase remained below inflation. This pricing policy and the delicate price adjustment were largely halted with the election of President Ahmadinejad for the years 2005–2014, so that water tariffs remained[5] constant for almost 10 years despite inflation of up to 34.7%. Without the adjustment of tariffs to inflation, the financial deficit caused by the Ministry of Energy amounted to the equivalent of about 12 billion US$ during this period.

During the presidency of Hassan Rohani, the first price increase was decided in 2013 after a long period of time and implemented repeatedly in the following years. However, the price increases did not even remotely match the real level of inflation in the country.

The extent to which current water tariffs cover the actual costs (investment and operating costs) cannot be answered. The tariffs also do not pursue cost-covering prices. The logic behind the tariff determination can be described in a nutshell as follows:

– The drinking water prices are to cover the pure operating costs of the water utilities. This is a goal that rural water companies have never achieved and which presents the urban water companies with major challenges every year.
– The water withdrawal costs for agriculture are to be limited to the monitoring costs of the water authorities and thus made available virtually free of charge.
– Tariffs for the supply of water to industry are often subject to negotiation. The price fluctuates according to the financial strength of the industry or depending on the regional water authority.

In summary, it can be said that Iranian water companies and water authorities cannot maintain their operations without annual state subsidies. At the same time, cost-covering tariffs for water are hardly conceivable in Iran's current economic

[4]"Economic Policy in the Iranian Energy Sector—Root of the Challenges in the Water and Energy Sector" in: The World of Economy, July 16, 2018. Figures and data in this section are taken from the same article.

[5]www.cbi.ir (accessed Feb 2020).

system. It is therefore not surprising that hardly any of the measures planned by the Ministry of Energy can be implemented in the time allocated.[6]

After this outline of the water sector, the next chapter uses the results of the futures research study conducted by the Center for Strategic Studies of the Iranian presidential office to better understand the sociopolitical role and significance of water resources.

3.3 Water and the Future of Iran

The "Iran's Future 1396 Study" was carried out from September 2016 till March 2017 by the Ayandehban Research Group under the supervision and guidance of the Center for Strategic Studies of Iran (Center for Strategic Studies 2017).[7] The main objective of this project was to recognize the key social, political, economic, and environmental uncertainties that Iran and Iran's society would face in 2017. The results included a list of 100 main issues and challenges for the year. As a national institute and through the medium of this project, the Center for Strategic Studies attempted to explore possible future prospects that could be presented to Iran and Iranians in a heuristic way, without any bias or prejudice. The methodology of "Iran's Future 1396 Study" was designed in six steps: Problem Identification, Problem Solving, Selection of 100 Problems, Problem Rating, Determining Key Uncertainties, and Scenario Planning. Indeed, this project was one of the first experiences in the country in publishing future scenarios by a think tank.

The study was based on past and contemporary data and evidence, as well as on experts' and citizens' opinions. Experts' opinions were involved in the process of identifying the future issues in four ways. The first was the implementation of expert panels in 11 thematic areas to identify issues and challenges of Iranian policymaking. Provincial round tables[8] were the second source of access to experts' opinions. Thirdly, online surveys were conducted to collect the opinions and comments of academic experts. And last, seven specialist task groups were involved in the research activities. In addition, citizens' surveys were conducted through online questionnaires and social media to collect citizens' opinions. The review of media headlines and contents for the year 1396 were another source of the data used in this research. The opinions of the experts and citizens as well as the media contents were combined to determine the top 100 issues and challenges of the year 1396.

[6] Cf. Chap. 4 "Objectives and performance in the water sector" (Ministry of Energy 2018: 236).

[7] The year 1396 in the Persian calendar corresponds to the time span from March 2017 to February 2018 of the Gregorian calendar.

[8] Provincial round tables consist of governmental and academic experts as well as different stakeholders such as entrepreneurs, producers, trade unions, charity organizations, and social and cultural stakeholders.

The importance of this study lies in its scientific approach, the selection of scientific research methods, and the participation of all relevant stakeholders and political actors and decision-makers in round Tables (27 provinces out of 32 provinces) to prioritize the challenges. Furthermore, the study is politically relevant and has been noted with interest by policy makers at the national and provincial levels.

3.3.1 The 100 Most Important Challenges Facing Iran

"Several thousand" challenges could have been collected according to the authors of the study. In a second step, these were elaborately weighted, prioritized, and reduced to 100.[9] The first 19 challenges have an importance level of over 80%. A further 43 challenges are rated with an importance of 70–80% and the remaining 38 with a relevance of 55–70% (ibid.: 31 f.).

Among the top ten at the national level, the "reform of the economic system" receives the highest relevance with 92%, closely followed by the "solution of the water crisis" with 90%. The respondents thus give greater importance to the water problem than, for example, unemployment, corruption, or a lack of future prospects. In seventh and eighth places, the challenges surrounding the dust crisis (due to increasing desertification and the drying up of various wetlands) and various consequences of the water crisis rank before poverty and economic crisis with 85% and 84% respectively. This means that three of Iran's ten most important challenges are directly or indirectly linked to water.

This prioritization of challenges naturally varies from province to province. In the province of Isfahan, the four most important challenges identified were (1) the water crisis, (2) the dust crisis, (3) the dangers of social media and the Internet and (4) the reform of the economic system (ibid.: 34).

The importance attributed to the water crisis also depends on the age of the respondents. While respondents born between the 1950s and 1980s rank the water crisis among the top five national challenges, it is not among the top five priorities of those born in the 1990s.[10]

Comparing the prioritization by sector or stakeholder leads to interesting results. For stakeholders from the environment, health, society, economy, and science sectors, the water crisis is one of the top three challenges facing the country. For stakeholders from politics and culture,[11] the water crisis and the dust crisis are not even among the top seven challenges mentioned. It is precisely the actors from politics and culture who should spearhead a sustainable water sector. Since the

[9]For the methodology of prioritization, see Center for Strategic Studies (2017: 25 ff).

[10]However, respondents born in the 1990s cite the dust crisis as the most important challenge (ibid.: 36–37).

[11]In Iran, the cultural sector includes religious and other institutions.

Table 3.2 Trends in seven sectors examined

	Economy	Politics	Culture	Society	Science	Environment	Health
Worse	32.9	37.9	36.4	43.2	11.4	**64.6**	47.3
No change	37.9	47	55.5	49.5	52.7	26.8	52.7
Better	29.2	15.1	8.1	7.3	35.9	8.6	0
	100	100	100	100	100	100	100

Source: Center for Strategic Studies (2017: 44)

Islamic revolution, a strong symbiosis between politics and Islamic culture has developed, which determines social change in Iran.

In summary, it can be said from the explanations that awareness of the problem of water has reached the heart of Iranian society and is considered one of the most important challenges for the future of the country. In the future, these challenges must be addressed more strongly by politics, and especially by religious cultural institutions, and translated into action.

3.3.2 *Challenges Facing Iran by Sector*

At this point, the significance and importance of the overall set of challenges by sector will be examined and assessed. To this end, the study divides the challenges into seven different categories: economics, politics, society, culture, environment, health, and science.

The people interviewed in the study see the problems in the environmental sector as the greatest challenge, with 78 points. This was followed by society (77 points), business and politics (72 points each), health (70 points), science and culture with 68 and 67 points, respectively. When asked about future trends in the individual sectors, 64.6% of those surveyed estimated that the environmental situation in Iran would deteriorate in the future. This is by far the worst trend value compared to the other sectors and the only sector in which more people expect a worsening trend than a steady one (see Table 3.2).[12]

The environmental sector was divided into nine themes in the study: water, renewable energy, biodiversity, forest, soil, climate, waste, NGO, and sustainable environment. Of the 488 environmental challenges identified, 156 are related to water, 109 to the sustainable environment, and 68 to climate. For each of the thematic areas of biodiversity and NGOs 31 challenges were named, for soil 29, waste 28, forests 25, and renewable energy with 11 challenges.

This means that the challenges in the environmental sector are seen to be the greatest in comparison with the other sectors and the forecast for future development is seen to be the most negative in this area. At the same time, of the challenges in the

[12] In assessing the statements, it should be noted that the study was conducted in 2017 and before the renewed US American sanctions.

environmental sector mentioned above, water-related challenges play the largest role (Center for Strategic Studies 2017: 62f.). This view is shared by the Iranian experts interviewed from the environmental sector as well as the experts from the other sectors (ibid.).

3.3.3 Consequences of the Water Crisis

The study also deals with the consequences of the water crisis, which have been grouped into four categories: Falling groundwater table, destruction of aquatic areas, soil erosion, and social crises (Center for Strategic Studies 2017:82ff.).

With declining groundwater stocks, the problem of massive soil subsidence, which now affects large parts of the country, is being addressed in particular. The land subsidence risks, namely damage to natural resources, infrastructure, and settlements, as well as the curvature of the water and wastewater and gas pipelines, have led to the long-term instability of power towers in many parts of Iran. Figure 3.4 shows the probability of land subsidence risk in Iran's alluvial aquifers due to the exploitation of groundwater resources. As can be seen, the subsidence risk is not limited to a specific region. Case studies by researchers in some of these areas have shown that subsidence even exceeds 30 cm/year. Haghighi and Motagh (2019), for instance, identified three distinct subsidence features in Tehran with rates greater than 25 cm/year in the western Tehran Plain, about 5 cm/year in the immediate vicinity of Tehran international airport, and 22 cm/year in the Varamin Plain to the southeast of the city of Tehran. Rafyi et al. (2019) also reported a 3.84 mm subsidence rate in the Mahyar Plain (southeast Isfahan) for each 20 mm drop of groundwater table according to the observed piezometric well data.

The prevailing period of drought in the last 10–15 years in Iran and the almost constant demand for water caused parts or whole lakes, rivers, and wetlands to dry up. In Iran, 43% of a total of 3.5 million ha of wetlands have almost dried up and have become hotspots for dust storms, as can be seen in Fig. 3.5, with negative consequences for the region. The standard index of Local Dust Events (LDE) for a period of 15 years (from 2002 to 2017) shows that in many parts of Iran where wetlands, lakes, and rivers have been drying up, this index number is higher than 20, indicating a large number of local dust events that affect these areas. In some areas, dust particles are associated with toxic and dangerous elements as well as salt particles that can endanger the health of people, the environment as well as agriculture. In their Chapter of this Edited Volume, Aghasi et al. also investigated the origin of annual dust storms produced in the Zayandeh Rud River basin as well as the spatial variations of heavy metals deposition rates in samples collected from the vicinity of the Gavkhuni wetland.

The lack of sufficient water for the forests and other flora leads to dehydration and massive damage to the native flora in Iran. More precise figures and information are scarce. However, the consequences, such as increased soil erosion, landslides, and floods, are realities that have an increasingly negative impact on people's lives.

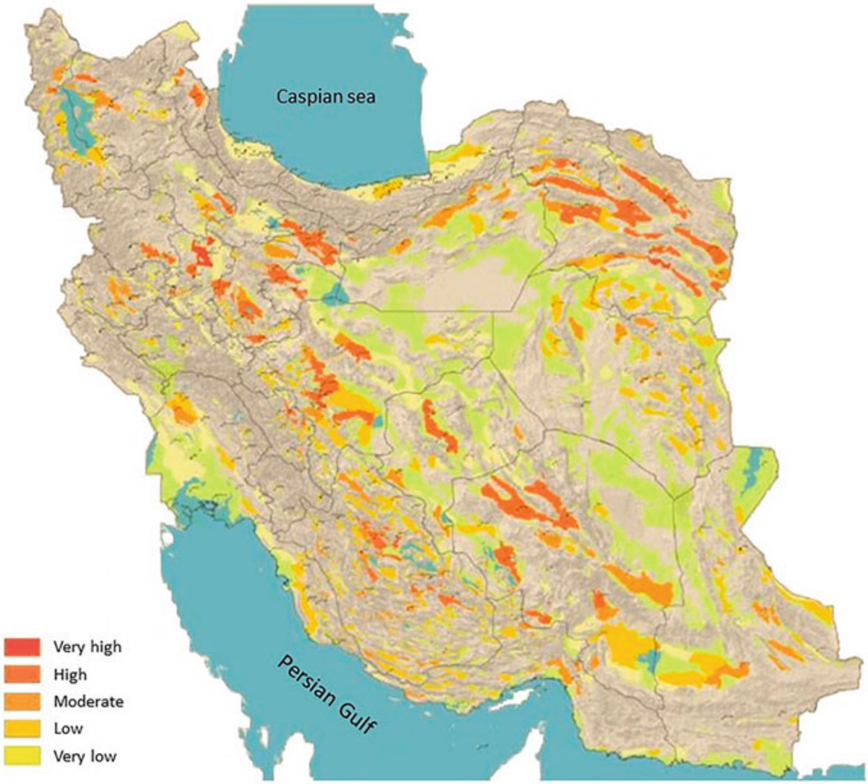

Fig. 3.4 The likelihood of land subsidence risk in Iran's alluvial aquifers due to exploitation of groundwater resources (Source: Geological Survey and Mineral Exploration of Iran)

In the study, the social crisis is associated with three issues: the dispute over water resources, migration movements, and agricultural reform. According to Iran's Third National Communication report to the UNFCCC (2017), water scarcity is one of the driving factors for urbanization in Iran, where around 75% of the population live in urban areas.[13] The findings of Golkarami and Kaviani Rad (2017) also pointed out that Iran will soon face severe social crises due to the high per capita decline in renewable water resources because of high water consumption. The water crisis in the Zayandeh Rud catchment area has also led to numerous economic, social, and environmental consequences, which affects not only the public and social security of the inhabitants of the watershed but also the national security of Iran and pose challenges such as the recession of agriculture, industry, and tourism, as well as demographic crises. The culmination of social crises in this catchment can be seen in the protests by the farmers in east Isfahan in reaction to water transfers from the

[13]https://www.statista.com/statistics/455841/urbanization-in-iran/ (accessed Feb 2020).

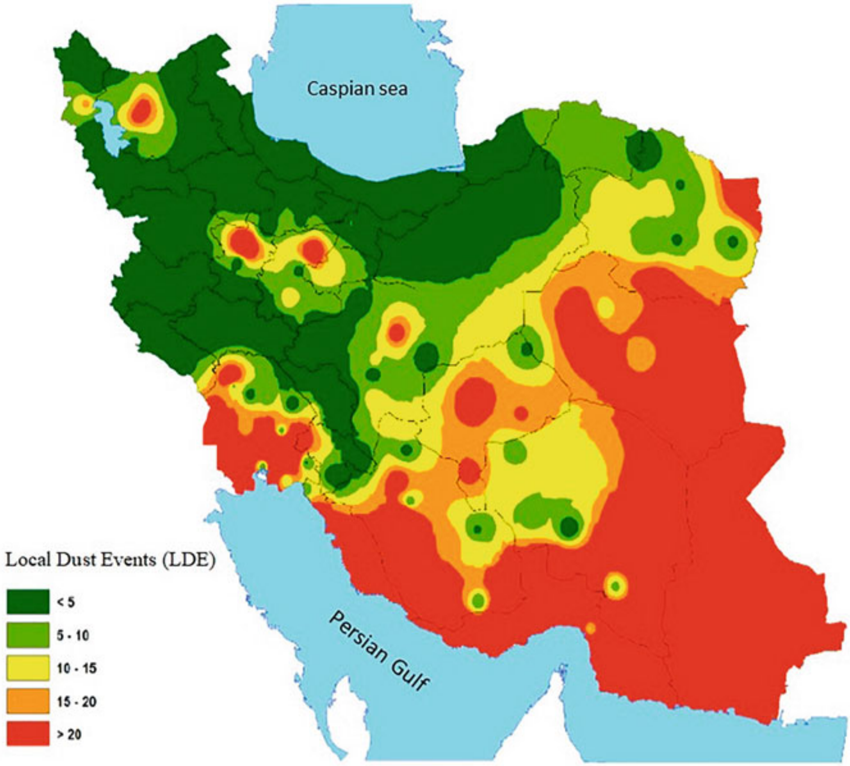

Fig. 3.5 Local Dust Events (LDE) index for the period of 2002–2017 (Source: Deputy of Human Environment, The Iranian Department of Environment)

basin, the protests of people in Khuzestan, to water transfers from the Karun Basin to the Zayandeh Rud and the protests of Chaharmahal and Bakhtiari province (see Fig. 3.6). In recent years, farmers in the eastern part of Isfahan have repeatedly protested the lack of water in the region and numerous clashes have taken place between the farmers and law enforcement.

3.4 Conclusion

Iran is pursuing sustainable water management on paper, according to the political guidelines and legislation that have been adopted. In reality, and based on a broad-based study commissioned by the Iranian government, the crisis over water is one of the country's most important problems.

As described in Sects. 2.2 and 2.3, the total annual demand of about 100 billion m^3 is compared to a quantity of renewable water resources of about 89 billion m^3.

Fig. 3.6 Protests by farmers from the eastern region of Isfahan against water shortages (**a**) and interruption of the water supply pipe to Yazd province (**b**) as well as the protests of people in the provinces of Khuzestan (**c**) and Chaharmahal and Bakhtiari (**d**) against water transfers from the Karun Basin to the Zayandeh Rud

For the sustainable development of water resources, the share of water used must not exceed 60% of renewable water resources (United Nations 2015). In this case, this would mean that the amount of water taken from renewable and fossil water resources would have to be reduced by 46 billion m^3 from the current 100 billion m^3 to 53.5 billion m^3.

Considering that agriculture today accounts for the largest share of water used in Iran (approx. 92%) and that Iran still has the phase of industrial development ahead of it, realistic solutions must be found in agriculture. With an estimated water demand of at least 8 billion m^3 for industry and drinking water supply and a further 2.5 billion m^3 for the protection of wetlands, agriculture has an estimated volume of 43 billion m^3, i.e., almost half of the water volume used by agriculture today (see also Table 3.1).

An almost halving of the agricultural water demand requires a very strong political will, flanked by a major financial effort, in order to be able to shape a socially just and sustainable process of change. The most important components of this change process are:

Replacing the political dogma of food self-sufficiency[14] with the recommended UN policy of food security (FAO 2006). The goal must be “availability at all times of

[14]Already after the Iranian revolution in 1979, the goal of food self-sufficiency was defined and gradually implemented. Since then, the political elite in Iran has used politics to try to cushion the

adequate, nourishing, diverse, balanced and moderate world food supplies of basic foodstuffs to sustain a steady expansion of food consumption and to offset fluctuations in production and prices." Whether the necessary amount of food is produced in the country or imported from abroad is of secondary importance. Such a policy shift must be supported by a major social program. Such a social program needs to:

1. Give new prospects to a large part of the approximately four million people employed in agriculture with an average age of over 50 years who have largely no further training (Mesgaran and Azadi 2018: 4).
2. Mitigate the additional costs for the general population caused by food imports, which have more than sextupled from US$ 4 billion to US$ 25 billion annually. These additional costs are estimated at US$ 300 per person per year (ibid.:20ff.).

At the same time, agriculture needs transformation and a significant increase in efficiency. This is linked to the establishment of new efficient management structures, from the selection of the crop cultivated to the national and international marketing of the products. In addition, significant efforts must be made to train farmers with the aim of successfully promoting new crops and methods of cultivation and the use of new technologies, in particular appropriate water-saving irrigation methods and greenhouses.[15]

In order for this transformation to achieve its goals—a socially acceptable halving of agricultural water demand—further political and legal decisions must be made and implemented. This includes in particular:

1. The adaptation of water legislation to the new water resource situation and a clear limitation of the withdrawal rights of farmers. In particular, the unlimited withdrawal rights of farmers in regions where there is now a lack of sustainable water supply or suitable soil quality must be abolished temporarily or completely against compensation.
2. An adjustment of water prices to actual costs or the value of the water. Water prices that reflect management and supply costs must be determined for all sectors—urban water management, industry, and agriculture—and increased gradually. Only in this way will users have sufficient motivation to reduce their consumption.

Without a gradual implementation of these policy reforms in the water sector, developed measures, such as the ideas and measures proposed by Raber and Reyhani in the chapter of this anthology on the Action Plan for the Roodasht Region of Raber and Reyhani can often prevent a deterioration of the current situation and do less to achieve sustainable development. And yet, the elaboration of such suggestions and

effects of international sanctions, to support farmers as bearers of the revolution and to emphasize their importance for the country.

[15]Even though the development needs and water-saving potentials of these technologies are very high, it is estimated that these technologies can reduce the water demand of agriculture by about 6.9 billion m^3 per year (Mesgaran and Azadi 2018: 14).

ideas for improvement is important in order to show those responsible in the affected regions the way out of a situation that seems hopeless. In this way, regional leaders can develop new visions and call on national policies to realize them. Only with this pressure from below can environmental and water policy in a country like Iran be brought to rethink.

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Chapter 4
Contemporary Water Resource Management and Its Role in Tackling Land Degradation and Desertification in Iran

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4.1 Introduction

The water shortage issue in West Asia is clear for scientists and governments. One of the most direct impacts of water shortage on these societies is the migration and displacement of thousands of people who have left their homes due to extreme climate events such as droughts. In one example, about 100,000 people had to emigrate from their homelands in northern Iraq to urban centers (Abdel Khaleq et al. 2012). In 2010, 800,000 Syrian people faced the same problem being affected by frequent droughts and mismanagement of water resources. Iran is also affected by the displacement of population due to climatic events. Water shortage in Iran is important (FAO 2008), and experienced by most of the inhabitants, especially farmers who are facing droughts directly. It was predicted that Iran will face water stress in the near future, with a serious reduction of water per capita ratio due to droughts and population growth (Madani 2005).

The current situation depicts a large variety of climates. In Central and Southern Iran, annual precipitations are low (e.g., less than 200 mm) that hampers agricultural developments compared to the Northern provinces which benefit from much higher precipitations, up to 2000-mm along the coastal regions of the Caspian Sea (Fig. 4.1). Indeed, 80% of Iran is classified as arid and semiarid zones. In addition, several climate change scenarios are talked about in the country. The annual average of precipitation might decrease by up to 20–25% of current values by 2050 (Keshavarz et al. 2014) with droughts becoming more frequent as a result. Over the last 30 years, precipitation has decreased while the temperature has increased

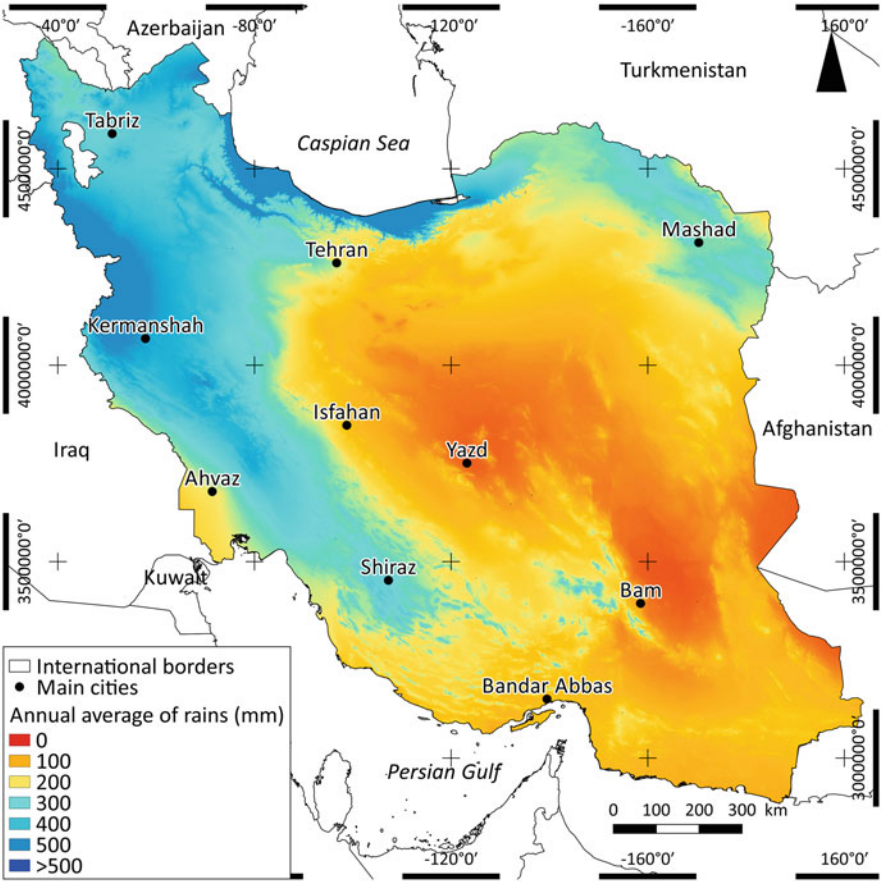

Fig. 4.1 Map of annual precipitation in Iran (Source: Karger et al. 2017a, b)

(Kousari and Ahani 2012). The level of groundwater will suffer from increasing extraction pressure and will be exacerbated due to the loss of groundwater discharge (Abbaspour et al. 2009).

One of the most critical sectors is agriculture that consumes 90% of the total water withdrawals in Iran (Faramarzi et al. 2010). Indeed, water productivity in the sector is low and if climate change scenarios occur, the situation will get worse. The supply for drinking water in urban and rural areas is another challenge. Although the country is well equipped with water supply systems, access to clean water might be difficult on the account of low precipitation (Keshavarzi et al. 2006). In addition, population growth, especially in metropolitan areas such as Tehran, will become a challenge (Keshavarz et al. 2005). There are 8.25 million inhabitants living in Tehran where domestic water consumption is around 316 L/day/inhabitant (Nuñez von Voigt and Mohajeri 2013). The use of recycled water for this purpose is necessary to provide water for the growing population (Moshtagh and Mohsenpour

2018) even in smaller cities in arid and semiarid zones (Mehryar et al. 2015). These zones have been desertified as a result of climatic factors (droughts and dust storms), population growth, pressure on resources (soil and groundwater), and mismanagement of water resources (Amiraslani and Dragovich 2010, 2011). Iran continues to face environmental issues that may threaten food security. One of the core aims of the Islamic Republic of Iran is food self-sufficiency, at least in cereals, in order to reach food security at the national level (Central Bank of the Islamic Republic of Iran 2015; Shariati 2016). Despite population growth and unprecedented events such as the severe drought of 2008, Iran has almost achieved its objective (Babar and Mirgani 2014; Amiraslani and Firbank 2017). Nonetheless, desertification and water shortages could hamper this achievement, since agriculture production in arid and semiarid zones deeply relies on water and irrigation. The Iranian agricultural system has been identified as very sensitive to droughts and desertification, similar to Iraq, Jordan, Morocco, and Syria (Shetty 2006). Rainfed agriculture is the most fragile sector if precipitation decreases, but the irrigated farms are also sensitive to climate change since the water storage is hampered by droughts.

In response to these critical challenges, the Iranian government has set up actions and interventions to tackle water shortage as well as land and forest degradation. Numerous studies have introduced and analyzed the policies since the beginning (Beaumont 1974; Foltz 2002; Amiraslani and Dragovich 2011, 2013; Madani 2014; Zargan and Waez-Mousavi 2016; Amiraslani et al. 2018). However, the present research aims at assessing contemporary strategies in Iran to cope with climate change. The first part of this work is to identify these strategies and analyze their efficiency through a literature review based on case studies in Iran.

For this purpose, recent studies, reports, and scientific papers have been used since numerous stakeholders are involved in this national challenge. Moreover, several case studies in Iran and relevant data have been compiled and analyzed here to review how efficient these interventions have been. This literature and database review seems to be necessary to identify the future challenges and feasible improvements of such interventions for the forthcoming decades. The chapter is organized into three sections. The first section deals with traditional strategies that still play a significant role, such as the construction of dams and groundwater management. The analysis of these historical strategies leads us to more contemporary interventions. In the second section, modern technologies in water management are discussed: e.g., reuse of wastewater, development of water use efficiency in agriculture, desalinization of seawater, and cloud seeding. The third section looks at the future of water management at the water users' levels.

4.2 Traditional Interventions

4.2.1 The Experience of Dams: From Massive Water Storage to Governmental Set Back

4.2.1.1 A Historical Intervention to Tackle Water Shortage

One of the most significant efforts in Iran has been the construction of dams. The water capacity of these dams varies, of which 316 are considered as large dams and Iran is regarded as one of the most dam-equipped countries in the world, in third place on the global scale (Madani 2014). The most arid provinces are more equipped with large dams compared to others in Northwest Iran where the precipitation is higher. The construction of dams is the responsibility of a centralized organization, the Ministry of Energy (MoE), aiming at increasing the water capacity and expansion of the irrigated farms in Iran (Tajrishy 2016). In addition, dams increase the capacity of electricity generation across the country (Tajrishy 2016). A total of 532 dams have been planned and 146 are already under construction. Dams will continue to play an important role in controlling water resources as well as electricity generation in Iran (Tajrishy 2016).

4.2.1.2 The Increase of Irrigation Areas and Water Shortage

The pace of dam construction has slowed down since 2006 but has reached a capacity of 32.24 km^3, which means the equivalent of 41% of the average renewable water in Iran (FAO 2008, 2017). The water capacity of dams drastically increased during the early 2000s, from 18.52 in 1990 to 31.81 km^3 in 2006 (Fig. 4.2). At the same time, the area of irrigated farms increased due to greater water storage in the large dams (Fig. 4.2). Hence, agricultural production has taken advantage of this water, strengthening food security in Iran.

Nonetheless, the efficiency of the irrigated farms meets some difficulties. Indeed, the areas equipped with ancillary irrigation systems to provide water to farmers is more important than the actual irrigated areas. The equipped areas seem to be beyond the planned water capacities of the dams (ICARDA 2017), and droughts continue to undermine water supply for dams. In provinces such as Markazi, Khorasan (North, Razavi, and South), Yazd, Kerman, Sistan-Baluchestan, and Hormozgan, only 44% to 62% of the equipped areas are actually irrigated. Meanwhile, dams cannot reach maximal capacities because of frequent droughts (Moridi 2017). The increasing number of dams in these provinces seems to have had an insignificant role in improving irrigated agriculture. As a matter of fact, 60% of the dams were empty because of the lack of precipitation in Iran in 2015 (ARUP 2016).

In addition, one of the most potent impacts of dams is the ecological consequences. The International Center for Agricultural Research in the Dry Areas (ICARDA) emphasizes the negative effect of water retention in dams on natural

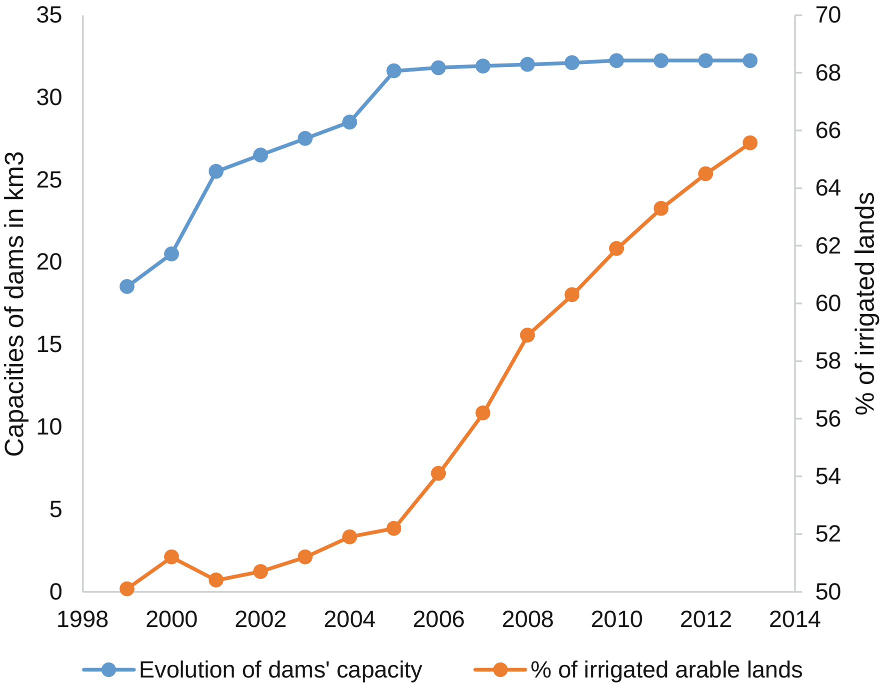

Fig. 4.2 Evolution of dams' capacity and irrigated lands in Iran: 1999–2014 (Food and Agriculture Organisation 2009)

water bodies such as lakes (ICARDA 2017). The lakes of Maharlu, Bakhtegan, Perishan (Fars Province), and Urmia (West and East Azerbaijan) have become dry partly due to the construction of dams (Fathian et al. 2015). These lakes are located in provinces where almost 100% of the areas equipped by irrigation systems are irrigated and dams are numerous.

4.2.1.3 Rescaling the Infrastructures: Alternative Options of Water Storage in Iran

On the one hand, dams have proved their efficiency in increasing the irrigation capacities of Iran (Saatsaz 2019). On the other hand, the ecological consequences have led to an increasing rate of soil salinization in some areas (Alizade Govarchin Ghale et al. 2017). In this research, the future challenges of the dam policy in Iran are outlined here. It seems that the government has shifted policy toward a considerable reduction in the construction of new dams (Khalaj 2015). Besides, if new dams are going to be planned in the future, two main challenges must be addressed: the improvement of site selection and the promotion of water diplomacy at the local level. Some scholars recommend new scales for dams: small dams and ponds

(Heydari et al. 2013). Indeed, small reservoirs are more efficient in controlling floods and providing water at the local scales. The scope of these dams, already experienced in other countries such as Lebanon, Tunisia, Morocco, Algeria, or Greece (El Hage et al. 2015; Selmi 2000; Albergel et al. 2004; Habi and Morsli 2011), becomes local instead of regional and the remaining unexploited and relevant streams would be enhanced.

4.2.2 The Priceless and Free Groundwater: The Necessity of Water Accounting

4.2.2.1 Current Measures to Control a Sensitive Water Resource

Historically, the use of groundwater has always been an answer to cope with low precipitation and surface water in arid and semiarid countries. In Iran, the agricultural sector particularly relies on groundwater: 55% of the irrigated farms use groundwater (FAO 2009). Gradually since the 1960s, the traditional Qanat has been replaced by water wells and especially electrified water wells. Such strategic water resources must be shared between land users as Iran's National Constitution states that water bodies are public and under the auspices of Government (Ehsani and Marani 2016). Nevertheless, groundwater is also owned as private property by farmers in order to irrigate their fields. The irrigators use a certain volume of water assigned by the Government and pump up the water from the aquifers for their private use (Nikouei and Ward 2013). This private use of groundwater requires a registration to the Ministry of Energy that delivers the authorizations to pump the water (ICARDA 2017), in order to control the implementation of wells. The permission is not delivered if farmers use water in a farm located in the under-stress water zones, where a new well would affect the existing users (Alasti 2013). The irrigator pays for this permission and for the electricity to pump up water. Nonetheless, other measures are also taken to control the use of groundwater. If the farmers are not qualified to use groundwater, the local water authorities will reduce the authorized water allocation (Ehsani and Marani 2016).

4.2.2.2 Increasing Yields and Irrigation Areas: The Multiplication of Water Wells in Iran

While the construction of dams and the authorization for pumping water have increased since the 1970s, the irrigated farm areas have also expanded. In the 1970s, the number of registered wells in Iran was estimated between 40,000 and 50,000 but reached 500,000 in 2006 (Collins 2017). According to the Ministry of Energy, total water volume extracted from groundwater using these wells is around 100 billion m^3 (ICARDA 2017). Nevertheless, there are significant numbers of unauthorized water wells in Iran. It has been estimated that these illegal wells

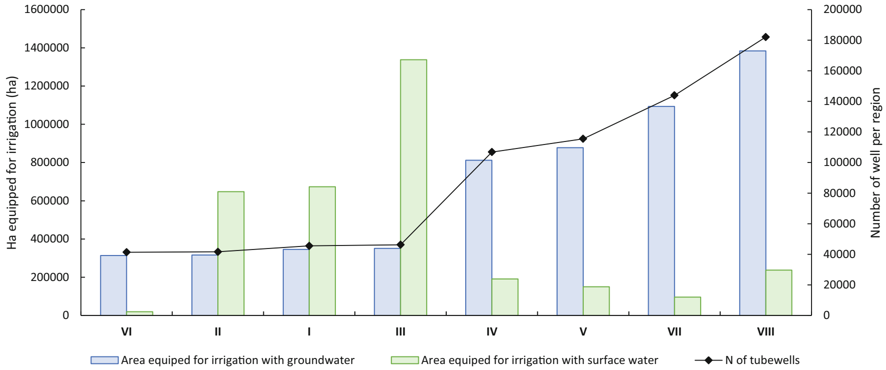

Fig. 4.3 Number of wells and area equipped for irrigation with ground and surface water in Iran (I: North Coastal areas; II: Azerbaijan; III: West border; IV: Fars and South Coastal areas; V: Kerman-Sistan-Baluchestan; VI: Isfahan; VII: Central; VIII: Khorasan) (FAO 2009)

represent one-third of the total wells in Iran (Collins 2017). If one well can irrigate 7.6 ha for groundwater irrigated lands (Karimi et al. 2012), and given the estimation of groundwater irrigated area per region assigned by the FAO (2009), our research found a total of 722,950 wells in the country (Fig. 4.3), including 241,000 illegal wells. Other research has estimated the total number of wells at 624,838 (Assadollahi 2009).

Khorasan provinces (Razavi, North and South) are the most equipped areas for groundwater irrigation with around 180,000 wells. Other regions such as Fars in the South of Iran also depend on groundwater with an extensive network of wells. One can easily find the majority of surface water irrigation lands in the North, Azerbaijan, and Western border even with sufficient annual precipitation.

These wells play a role in the overpumping of groundwater, with a water table drawdown of 0.4 m per year (Closas and Molle 2016). This challenge is a top priority for the country. In 2015, the Supreme Water Council of Iran set up a protection system for extraction of groundwater by the installation of a volumetric system paid by the farmers (Ehsani and Marani 2016). It is difficult to analyze the efficiency of this recent policy and further studies could assess its relevance. This law strengthens the "Groundwater Resources Preservation Act," approved in 1966 and establishes a modern answer to this challenge (Nabavi 2017). Another measure was to restrict the exploitation of some fragile aquifers in Iran, where the water drawdown was more than 0.50 m per year (Closas and Molle 2016). In total, out of 609 aquifers, 67 are regarded to be in critical condition (Assadollahi 2009). As has been discussed before (Amiraslani and Dragovich 2011), such overexploitation of underground water resources has had direct effects on the desertification of fragile lands across Iran.

4.2.2.3 Strengthen the Control of Illegal Water Wells and Consumption

Several strategies are mentioned for Iran to cope with the groundwater crisis in the next decades. Water-related authorities will continue to block the illegal wells as well as to improve the knowledge of water stakeholders and farmers (Closas and Molle 2016). Nonetheless, other options are being studied such as the Smart Energy and Water Meter (SEWM) (Ehsani and Marani 2016). This technology controls and monitors the consumption of electricity and water from the well's pipes. SEWM calculates water flow through measuring instant electro-pump's electricity parameters according to the pre-defined pump's curves (Jahromi et al. 2014). When the consumption of energy reaches its climax and a critical level determined by water authorities, the power is cut. Currently, 1000 SEWM are operating and enable the conservation of 60,000 m^3s per day in Iran (ibid.). In addition, SEWM records relevant data to be used by water-related authorities and scientists to track the trend and state of local groundwater.

4.3 Use of New Technologies

4.3.1 Usage of Waste Water: A Minor Share of Water with Significant Capacities

4.3.1.1 Waste Water Treatment Initiatives in Iran

Concurrently, alternative technologies and infrastructure are being used to mitigate freshwater shortage. For instance, recycled sewage is a promising action to improve the conservation of water (Hassanpour Darvishi et al. 2010). Iran already uses recycled sewage water to provide clean water to the cities and, to some extent, to irrigators in the suburbs (Moghadam et al. 2015). Sewage treatment has existed in Iran since 1961 and the government has set up precise national mandates to reuse water (Rahimi et al. 2018). They include the Usage of Wastewater Law, The Equitable Water Sharing, The Environmental Conservation Law, The Five-Year Development and Economic Plans, The Regulation of Prevention of Water Pollution, and The Regulation of Usage of Recycled Water Resources (Ministry of Energy 2000). Iran is equipped with 129 water treatment plants (Tajrishy 2016). Furthermore, the reuse of water is particularly beneficial for irrigation of vegetables that will be enriched by organic nutrients dissolved in wastewater (Rahimi et al. 2018). Indeed, the use of wastewater enables farmers to reduce the application of fertilizers. However, there have been reports mentioning the ignorance of water quality standards and inappropriate usage of wastewater for irrigation of small farms (Hassanpour Darvishi et al. 2010). Such misappropriations of high-level contaminated organic matter affect the quality of crops and the health of consumers.

4.3.1.2 The Relevance of Treated Water and Usage Risks

Urban areas are more equipped with wastewater infrastructure than rural areas and in fact, 30% of the urban population takes advantage of recycled water (Ministry of Energy 2000). In 2006, about 3539 million m^3 of water were treated in urban areas compared to 740 million m^3 in rural areas (Ministry of Energy 2000). The Food and Agricultural Organisation (FAO) estimated that over 345 million m^3 of municipal wastewater, including 0.32 million m^3 for irrigation purposes, was used in 2009. In addition, out of 116 million m^3 of wastewater collected by municipalities only 0.88 million m^3 was actually treated, meaning that a significant share of wastewater is released into the surrounding environment. In Iran, the usage of treated waters might be prohibited for drinking purposes on account of low quality (Moghadam et al. 2015). According to several studies in the country, there is a low level of concentration of heavy metals but with a high rate of coliforms surpassing the permitted limits (Nikbakht-Shahbazi and Saadatian 2014; Rahimi et al. 2018). Although the reuse of wastewater can improve soil fertility, it can concurrently contaminate the aquifers with Nitrate.

4.3.1.3 Future Infrastructures for Waste Water Treatment

Human health and the pollution of aquifers seem to be the most challenging issues for wastewater management in the future (Hassanpour Darvishi et al. 2010; Moghadam et al. 2015; Rahimi et al. 2018). Therefore, previous research and databases are necessary to study the quality of such water resources to be used by stakeholders to lead these researches (Nikbakht-Shahbazi and Saadatian 2014). The success of Artificial Wetlands (AW) for small cities such as Dezful inspires a national policy to enhance the sustainable treatment of wastewater resources (El Zein et al. 2016). In addition to numerous environmental benefits (wildlife habitat and protection of water bodies), artificial Wetlands are an efficient method of water treatment. However, as wastewater resources with low and insufficient quality are illegally used for irrigation, the control of water use is a key issue in the country. The quality and quantity of such sources of water should be protected, strengthened, and controlled in order to maximize its relevance (Valipour and Singh 2016; Danesh et al. 2010; Rezapour et al. 2011).

4.3.2 A Well-Known Low Water Use Efficiency: Review and Perspectives

4.3.2.1 Toward the Pressurized Irrigation System

One of the most significant challenges in Iran is the improvement of water use efficiency, especially in agriculture (Madani 2005). Thereby, governmental policies aimed at changing Iranian irrigation systems toward expanding pressurized irrigation techniques such as drip or sprinkler for the improvement of water use efficiency as one of the flagship projects in Iran (Soltani 2013; Ehsani and Marani 2016). The other intervention of the government is to replace open-air water canals with pipes for supplying irrigation water. High temperatures, evapotranspiration, and wastage of water are the main issues for agriculture in most of the watersheds characterized by arid and semiarid climates in Iran. The Iranian government strongly supports modern irrigation systems. As such, between 60% and 85% of the total costs to install irrigation systems are subsidized by the government, enhancing the installation of more efficient irrigation systems.

4.3.2.2 Low Efficiency of Irrigation Water Use in Iran

The water use efficiency of irrigation is only around 35% in Iran (Saatsaz 2019). Indeed, current irrigation systems, such as non-concrete furrows or gravity systems, hamper irrigation efficiency (Jackson et al. 2010). One can notice variability of irrigation efficiency between Central and Northern Iran with wetter climates ranging from 35% in Isfahan Province to 65% in Guilan. Irrigation efficiency depends on the availability of water sources as well as irrigation systems and management (Keshavarz et al. 2005). On the account of traditional irrigation systems, such as furrow and borders, irrigation efficiency remains low in Central Regions. Conversely, the Guilan Province in the North has the highest level of irrigation efficiency due to the expansion of modern irrigation systems and significant precipitation. However, studies show that modern irrigation systems can increase water and energy needs (Gómez and Gutierrez 2011).

4.3.2.3 Accessibility to Irrigation Systems and Tracking Water Consumption

In addition to concrete furrows to limit loss of water, massive investments are required to equip farms with modern irrigation systems in Iran (Karimkoshteh and Haghiri 2004; Jafary and Bradley 2018). The industry of irrigation is thus at the forefront of this challenge, but the accessibility of farmers to such techniques should be supported. Indeed, this equipment is costly for modest farmers, but agribusiness farms are able to fund it. Besides, one of the key features is the development of a relevant database on water use, especially on irrigation efficiency which is currently unavailable in Iran (Jackson et al. 2010; Rad et al. 2017; Jafary and Bradley 2018). For instance, the estimation of yields is necessary to compute irrigation efficiency and remote sensing methods could play a significant role in this purpose. Such a database would be more interesting if it covered the field scale rather than regional or provincial scales (Jackson et al. 2010). From this database, scientific stakeholders could lead to relevant research and calibrate projects more efficiently (Jafary and Bradley 2018). Such investments could enable the country to decrease its water consumption, especially in the agriculture sector. Therefore, *Iran Vision 2025* targets a decrease in water consumption from 92% (current value) to 87% of the water resources in agriculture (Moghadam et al. 2015).

4.3.3 *Seawater Desalinisation: A Future Perspective to Tackle Water Shortage in Iran*

4.3.3.1 Advantageous Seawater Bodies in Iran

Surrounded by two significant water bodies—the Caspian Sea in the North and the Persian Gulf in the South—Iran can explore another possibility of tackling water shortage and desertification through seawater desalinization. Iran started to implement small infrastructure of desalinization in the South in the 1960s (Emami et al. 1966). The South of Iran is the most equipped region since water shortage is prevalent in the region, mainly in Sistan-Baluchestan province where the construction of Chabahar–Konarak desalination plant with a capacity of 35,000 m^3 per day was initiated. In 2021, this project will be completed and will provide fresh water to the region. Iran will be able to produce 3.5 billion m^3 of desalinized seawater within the next 10 years (Gorjian and Ghobadian 2015). For this purpose, there are two main methods to desalinize water: thermal evaporation and membrane-based separation (Elimelech and Phillip 2011), and Iran can produce around 120 million m^3 every year with these methods (Gorjian and Ghobadian 2015). Iran has not yet reached its full capacity of desalinized seawater and it is estimated that a total of 645,060 m^3/day will be desalinized (ibid.). This level of production will improve the share of desalinized water resources in agricultural, industrial, and domestic use by around 9%. Currently, Iran is able to desalinize around 500,000 m^3/day and 215 million m^3/year (Tajrishy 2016).

4.3.3.2 Water Consumption in Iran: A Small Share of Desalinized Water

However, these figures hide another reality: the share of desalinized water is not considerable in Iran, compared to other water resources. According to FAO Office in Iran (FAO 2009), agriculture, industries, and domestic consumers used 0.2 km^3 of desalinized water, while groundwater and surface water represented 53.1 km^3 and 40 km^3, respectively. Therefore, it shows that Iran does not strongly rely on desalinized water, contrary to its neighboring countries that highly depend on desalinization water: Bahrain (63%), Qatar, and Kuwait (around 70%) (World Bank 2018). Nevertheless, the efficiency of water desalinization is marred by its high energy consumption and cost with a global average of 1.96 \$/m^3 depending on the size of the plants (Karagiannis and Soldatos 2008). Current installations of water desalinization require a significant amount of fossil fuel and increase air pollution with gas emissions (Younos 2005).

4.3.3.3 Solar and Wind Energy: A Relevant Opportunity for Water Desalinization in Iran

The establishment of 150 new plants are foreseen in the future (Gorjian and Ghobadian 2015). A key challenge is to convert the current desalinization with fossil energy to new technologies, more sustainable, and adapted to Iran. As significant solar radiation is received in Iran (Alamdari et al. 2013) solar desalinization technologies could be one of the most promising technologies to provide and treat seawater, especially in the Persian Gulf (Gorjian and Ghobadian 2015). The annual average of solar radiation is about 15 kWh/m^2/day (Hosseini and Soltani 2016), compared to the global average: 4.4 kWh/m^2/day (Aksoy 2011). Solar energy is used to distillate water. Other Iranian studies develop the process of using abandoned gas or oil wells to desalinize water using ground heat. Around 565 m^3 of desalinized seawater can be produced per day in these wells and the energy savings are significant (Noorollahi et al. 2017). Regarding water (not exclusively seawater) desalinization, Iran is also establishing reverse osmosis desalinization plants using renewable energy. In Davarzan (Khorasan), Maleki et al. (2016) showed that the costs of desalinization are high due to energy storage in batteries. Nonetheless, battery recharging with solar and wind energy enabled significant savings. Therefore, the combination of solar and wind energy for water desalinization should be promoted in Iran, especially due to numerous locations with high renewable energy potential (Alamdari et al. 2012).

4.3.4 Cloud Seeding in Iran: A Lukewarm Experience

4.3.4.1 Cloud Seeding Campaigns to Date

Cloud seeding can be mentioned as an alternative process for tackling water shortage and desertification. The main purpose of cloud seeding is to enhance the amount of precipitation. The first experiences of cloud seeding in Iran began in the 1960s in Karaj and Jajrood Rivers, located adjacent to Tehran (Omidvar et al. 2014). In the 1990s, Alborz and Central mountains were then selected for cloud seeding. To perform such technology, the National Cloud Seeding Research Center (NACSER) was created in Yazd in 1997, under the auspices of the Ministry of Energy. The NACSER is the only national center in charge of cloud seeding and leading several projects, in collaboration with the Russian Central Aerological Observatory (NACSER 2018). Equipped with UAV, aircraft, and radars, NACSER is in charge of executing cloud seeding projects in Iran. Until now, NACSER has lead projects in 11 provinces in 13 years.

4.3.4.2 Various Results and Efficiency of Cloud Seeding

A primary cloud seeding campaign launched in several locations in 1967 was considered successful in tackling a drought but lasted only 6 years (Rogers 2009). More recent projects have shown various efficiencies. Nonetheless, cloud seeding can increase the amount of rainfall. According to a research finding (Zoljoodi and Didevarasl 2013), the intervention in the watershed of Gav Khuni was the most efficient with an increase of 46.4% of natural precipitation. In addition, the provinces of Yazd and Kerman have suitable atmospheric conditions to pursue cloud seeding in the future (Omidvar et al. 2014). However, the same technology shows uneven results: 18.9% in the Zagros mountains. Indeed, rainfall enhancement can vary from 1% to 52% in Iran (Hosseinzadeh and Javanmard 2012) and dissimilar results might hamper the relevance of cloud seeding in many areas. Some failures in this process have led the Iranian and international scientists to give up on cloud seeding such as in the case of the restoration of Urmia Lake (United Nations Development Programme 2014).

4.3.4.3 The Accuracy of Cloud Seeding Models: The Condition of Success

One of the most critical factors for guaranteeing the efficiency and relevance of cloud seeding is careful and precise feasibility studies before the implementation of any operation (Zoljoodi and Didevarasl 2013; Omidvar et al. 2014). Weather Numerical Models such as the Global Weather Model (WRF) or the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) are being used by NACSER (NACSER 2018). These models enable scientists to locate the most suitable sites for cloud seeding, especially in arid and semiarid zones. In addition, the use of drones might be increased over the next decades in order to fill the lack of feasibility pre-studies before operating cloud seeding (The Iran Project 2018). Drones will be used to fly in the given zones before cloud seeding; in order to record real-time data such as temperature, cloud density, and wind speed. Therefore, local authorities will improve their knowledge about the best time and the location to maximize the efficiency of cloud seeding.

4.4 Water Users' Level

4.4.1 Charging Irrigation Water: A Debate in Iran

4.4.1.1 Current Pricing of Water in Agriculture

A growing use of technologies and the expansion of infrastructure are considered direct socioeconomic measures to tackle water shortage and desertification. In Iran, water bodies are public property according to Article 1 of the Nationalization of Water Resources ratified in 1968 (Alasti 2013). It has been admitted by Iranian scientists that water pricing might increase water use efficiency, especially in agriculture (Esmaeili and Vazirzadeh 2009; Nikouei and Ward 2013; Ehsani and Marani 2016; Collins 2017). Indeed, water is almost free for farmers who only pay for maintenance, gasoil, electricity, and equipment for pumping groundwater (Nikouei and Ward 2013). Groundwater was supposed to be charged between 0.25% and 1% of the cultivated crop value, but the Parliament Law of 2004 stated that groundwater is free of charge. The law of Fair Water Distribution (1982) introduced pricing on water for any kind of use. The price of m^3 was calculated according to the quantity and quality of water consumption (Ehsani and Marani 2016). For modern agriculture, 1 m^3 of surface water costs 3% of the crop value on the market; 2% for semi-modern agriculture, and 1% for traditional agriculture (French Embassy 2018). The amended Law in 1990 foresees penalties for excessive use and overexploitation of water: extra fees are collected up to 1.5 times the normal price (Ehsani and Marani 2016). This charging system is easier to set up than calculating the amount of water consumed by each individual farmer on a national scale (ibid.).

4.4.1.2 Water Pricing in Favor of Groundwater Exploitation

The efficiency of water pricing is highly related to water use efficiency, as previously introduced in this research. Iranian farmers have increased water use, not through surface water, but intensive irrigation in order to reach profitable yields (Nikouei and Ward 2013). Hence, a significant amount of water is wasted and over-irrigation is a frequent phenomenon, especially because of inefficient irrigation systems such as furrows. Farmers and irrigators perceive water as an abundant and inexhaustible resource (Esmaeili and Vazirzadeh 2009). The price per m^3 needs to be higher to enhance water use efficiency (Perry 2001) and modern water meters on pipes might tackle the overuse. In a study titled: "Iran's energy scenarios on a 20-year vision," a reform of subsidies started in 2010, mentioning the increase of prices of energy such as petroleum, natural gas, electricity, and water (Chaharsooghi et al. 2015). Instead of supporting energy resources, the private sector takes advantage of public loans for converting their infrastructure into energy saving technology. However, it seems that water price has not increased significantly through this reform. Therefore, this research uses the evolution of consumer electricity price (necessary to pump groundwater), to assess whether or not Iran is moving toward new energy pricing (Fig. 4.4).

From 1990 to 2014, the consumer prices of household, public, and industry increased by 80%, 71%, and 122%, respectively. Nonetheless, the price of agriculture usage only increased by 37% between 1990 and 2014. Hence, the agriculture sector was affected less by expensive electricity, and groundwater extraction was favored by farmers. Overall, the pricing of m^3 of water and kWh of electricity used by irrigators are not limiting factors for intensive groundwater usage.

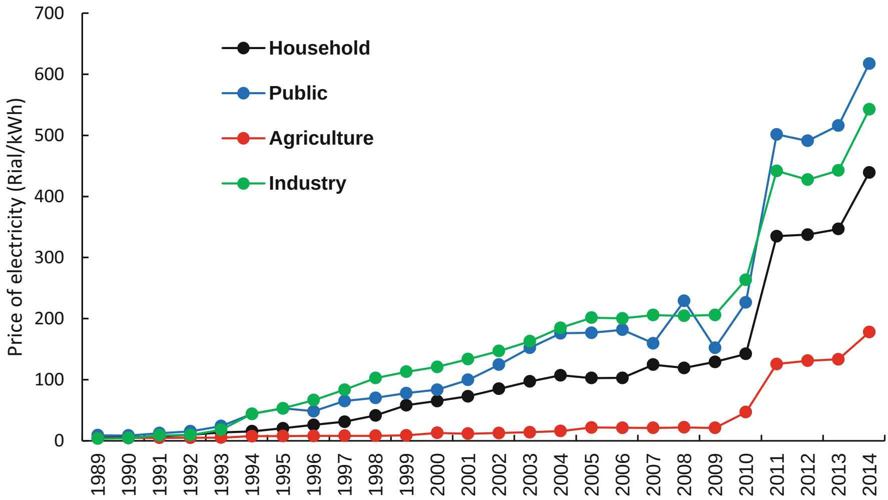

Fig. 4.4 Evolution of consumer electricity price per sector in Iran from 1989 to 2014 (Iran Open Data 2017)

4.4.1.3 Consequences of Increasing Water Pricing

Water pricing appears to be another challenging issue for tackling water shortage and desertification. It would be a relevant policy to decrease the exploitation of groundwater, but also on account of its political aspect. Conflict with rural farmers regarding water pricing could lead to social disturbances. It is politically challenging to save water through pricing, even if it seems to be a suitable answer (Perry 2001). The charges for water must be suitable and affordable for irrigators; otherwise, a drastic increase of consumer price would be useless. Water price should at least enable farmers to recover the costs of production (Nikouei and Ward 2013). A study has calculated the maximal price farmers could afford per hectare for the following crops: onion, tomato, watermelon, cucumber, horticulture crops, almond, pomegranate, lime, and grape (Nikouei and Ward 2013). One should mention the experience of the Murray River, Southern Australia (Bjornlund and MacKay 1998). Irrigators accepted paying additional fees for water from other irrigators with low outputs per unit of water on account of their farms' profitability. Most of these farmers were already using water effectively. Therefore, they could maximize their incomes per unit of water. Without such an advantageous use of water, it seemed impossible for farmers to accept water pricing.

4.4.2 A Containing Challenge for Future Water Management: Participatory Water Management

4.4.2.1 Legal Tools in Favor of Participation in Environmental Management in Iran

This research ends current water challenges and policies with a broad-based paradigm: participatory water management is related to each intervention already mentioned in this chapter. Once again, the prism of technology is not the only answer to water shortage and desertification (Jafary and Bradley 2018). The inclusion of local or traditional knowledge on water resources should be included in the decision-making process. This might happen in collaboration with local stakeholders such as water users and government agents through a holistic approach (Mays 2013). In Iran, the role of participatory water management began in the 1960s and was strengthened after the Islamic Revolution in 1979, although it is still not well-institutionalized (Horlemann and Berenji 2017). Under the White Revolution of Iran in 1963, a centralization of the decision-making process and nationalization of resources hampered participatory water management and the government took independent decisions.

4.4.2.2 The Relevance of Local Stakeholders' Involvement in Environmental Projects in Iran

Private, semipublic, and local initiatives seem to be increasing regarding water projects in Iran (Omid et al. 2012). For instance, Water Users Associations gather irrigators to improve water efficiency, productivity, and sustainability through the association of private farmers. Government delegates water management to local stakeholders. Another example of participatory management in Iran is the recent Coordinating Council for Integrated Management of the *Zayandeh Rud* Basin (2014), shared between three provinces: *Chaharmahal-Bakhtiari*, *Yazd*, and *Isfahan* (Horlemann and Berenji 2017). This authority mission is about to improve the collaboration between different Ministries (Energy, Agriculture, and Industry) and local users for watershed management. However, the literature reports limitations in the participatory process. There is a lack of power and attitude among the Water Users Associations, limiting their efficiency (Omid et al. 2012). Indeed, participatory water management still remains centralized in Iran. Hierarchical levels and top-down decision-making dominate this process as in many other countries in the world (Horlemann and Berenji 2017).

4.4.2.3 The Necessity to Apprehend Local Stakeholders' Expectations Before Their Involvement

The behavior of the different stakeholders should be studied (Jafary and Bradley 2018) based on ground data and socioeconomic surveys as conducted in Lorestan Province (Gholamrezai and Spehvand 2017). For this purpose, more frequent workshops on (a) irrigation and (b) participatory processes should be offered by water authorities. In Iran, several NGOs already play a significant role in this issue, by communicating with local stakeholders in order to calibrate water and agricultural projects at local scales. Nevertheless, participatory water management is difficult to set up and international projects such as the Integrated Water Resources Management of Zayandeh Rud has highlighted how time-consuming but valuable a participative approach can be (Integrated Water Resources Management 2017). Eventually, the experts of this project chose to set up participatory water management, on account of numerous, important and diverging points of view among local stakeholders, which needed to be discussed. Overall, and despite its difficulties, participatory water management is recognized as a very useful tool—equally beneficial for public agents and local water users—and it should be promoted in all water projects in Iran.

4.5 Conclusion

The aim of this study was to identify the current interventions for tackling desertification and water shortage and to assess their efficiency. The discussion of each intervention showed the necessity to pursue water saving efforts in Iran. On the one hand, the set back of some interventions is necessary, such as the development of large-scale dams or the overexploitation of groundwater for its detrimental consequences on water resources such as water level decline and salinization, as well as land degradation and desertification. On the other hand, water saving interventions need to go further, especially on water use efficiency and groundwater use control. These interventions are related to each other and the inefficiency of one of them could affect the others' efficiency. The combination of stakeholder participation and technologies such as SWEM or pressurized irrigation systems is relevant to tackling water shortage. Without any control of water, the irrigation efficiency and water use, in general, would hamper any effective attempted reversal of land degradation and desertification. It appears nowadays that a relevant management of surface water and groundwater is the first key point to tackle land degradation and should be favored instead of new artificial water resources such as cloud seeding and desalinized seawater. Some of the interventions are promising as shown in this chapter, especially on the water user's level: the efficiency of water use depends more on the users than traditional interventions and the use of technologies. Such an approach of water shortage can guarantee a sustainable, comprehensive, and integrated management of resources. In this regard, the case of Iran is an interesting and useful example since the country is experiencing numerous interventions to tackle its water crisis. These experiences can be beneficial for other countries in the region also experiencing water shortage.

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Part II
Water and Land Use Challenges in the Zayandeh Rud Basin

Chapter 5
Zayandeh Rud River Basin: A Region of Economic and Social Relevance in the Central Plateau of Iran

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Contents

5.1 Introduction

The Zayandeh Rud river basin with an approximate area of 26,920 km^2 is located on the central plateau of Iran. The Zayandeh Rud river basin has a variety of climates. Mountainous areas west of the basin with 1400 mm annual precipitation, and the central and lower areas with 100-mm annual precipitation have a dry climate. The Zayandeh Rud river, the only permanent river in the central plateau of Iran comes from the Zagros Mountains in the West and after 450 Km reaches the international Gavkhooni wetland south west of Isfahan. Uncertain precipitation, periodic precipitation fluctuations, and periodic dry periods are features of the Zayandeh Rud River Basin. 7.1% of the basin area is located in Chaharmahal and Bakhtiari province and 92.9% in Isfahan. The population of the Zayandeh Rud river basin was 3.97 million in 2006, and according to the 2016 census, the population of the basin has risen to

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4.47 million, of whom 97.8% live in Isfahan and 2.2% are located in Chaharmahal va Bakhtiari province (Mohajeri and Horlemann 2017).

Water scarcity during the last two decades has led to a continuous crisis in the Zayandeh Rud River basin. Continuity of this crisis, even during years with normal or more than normal precipitation rate, indicates that this crisis is neither temporary nor caused by drought. Despite severe water shortage in the Zayandeh Rud River Basin, it has a significantly important place in the national economy. The sectoral beneficiaries of the Zayandeh Rud can be listed as follows; 68% of national steel production, 8.5% of national power generation, 26% of petrochemical and refinery products, and 12% of national cement production, drinking water supply for five million people and water supply for the agricultural sector in 260,000 hectares of water cultivation (wheat, barley, sugar beet, cotton, corn, potatoes, and garden products).

5.2 Exchange of Surface and Underground Water Resources in the Zayandeh Rud River Basin

The Zayandeh Rud River Basin consists of closed basins. This means water loss from various usages will not exit the basin and is recycled in the basin. Table 5.1 shows the multiplier effect of water recycling in water balance in the Zayandeh Rud River Basin (Seckler et al. 2003; Ziaie 2011).

According to Table 5.1, although the total capacity of basin annual water is 2681 MCM, the total amount of water exploitation in various sectors is 5617 MCM. Despite traditional irrigation methods, multiple water exploitations have led to a high amount of irrigation efficiency on the scale of the Zayandeh Rud River Basin. According to the water balance, irrigation efficiency is 70%, which indicates water consumption with high efficiency (Zayandab Co 2008).

Table 5.1 Water balance in Zayandeh Rud river basin in 2006 (Zayandab Co. 2008)

Resources	Capacity (MCM)	Extraction	Capacity (MCM)
Renewable rainfall resources	2214	Underground resource extraction	3757
Entry to the basin (inter basin transfer)	647	Surface resource extraction	1860
Exit the basin and evaporate from the dam	180		
Total of real water resources in the basin	2681	Total extraction	5617

5.3 Interbasin Water Transfer to the Zayandeh Rud Basin

For centuries severe water shortage and population growth have led governments to the thought of interbasin water transfer. Records of this effort go back to the sixteenth century where the French ambassador, by the order of Iran's king, assigned Monsieur Genet to transfer water to the Zayandeh Rud River Basin from the nearest basin (Hosseini Abari 2000). The efforts at that time were unsuccessful and the first interbasin water transfer project was operated in 1954 and further projects were operated in 1985 and 2006. As shown in Table 5.2, the total interbasin volume transfer to the Zayandeh Rud River Basin reached 647 MCM. Despite the interbasin water transfer and increasing water resources in the Zayandeh Rud River Basin, due to the high population growth, renewable water per capita was reduced (Fig. 5.1). According to Fig. 5.1, in 1931 the amount of renewable water per capita was 4428 m^3, in 2016 despite the 647 MCM transfer to the basin, renewable water per capita has reached 640 m^3.

Table 5.2 Interbasin water transfer to the Zayandeh Rud river basin projects

Interbasin transfer project	Operation year	Normal amount annual transfer (MCM)
Koohrang 1	1954	293
Koohrang 2	1985	224
Cheshme Langan - Khadangestan	2006	130
Total		647

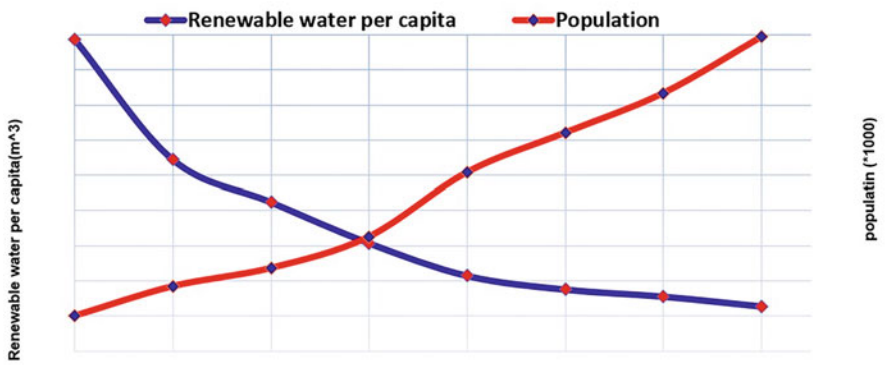

Fig. 5.1 Renewable water per capita reduction due to population growth after interbasin transfer to the Zayandeh Rud river basin

5.4 Constructing the Zayandeh Rud Storage Dam

The Zayandeh Rud hydrological regime is such that more than 70% of the watering volume occurs in winter and spring when the agricultural needs are low (Table 5.3). In summer and autumn, with higher needs, the water volume cannot satisfy the agricultural needs.

Before construction of the Zayandeh Rud storage dam, some parts of the spring and winter runoff was out of reach. During wet years (years with precipitation of 2000 mm and more in the western mountainous parts), water output volume from the basin was significantly high. For example, during the years 1949, 1950, and 1954 water output volume from the basin were 1901, 1139, and 930 MCM.

According to Fig. 5.2, due to non-compliance of the Zayandeh Rud watering regime with agricultural watering needs, major parts of the river were non-operational. Construction of the Zayandeh Rud storage dam with the capacity of 1400 MCM in 1970 maximized the amount of operational water and changed the natural watering regime of the river.

The Zayandeh Rud Dam, with the ability to store the total annual river yield, has increased the capacity of usable water on one hand, and has eased the situation for

Table 5.3 Average seasonal water discharge from the Zayandeh Rud dam (Zayandab Co. 2016)

Zayandeh Rud annual water discharge	Spring	Summer	Autumn	Winter
Volume (MCM)	450	93	104	203
Seasonal percentage	53%	11%	12%	24%

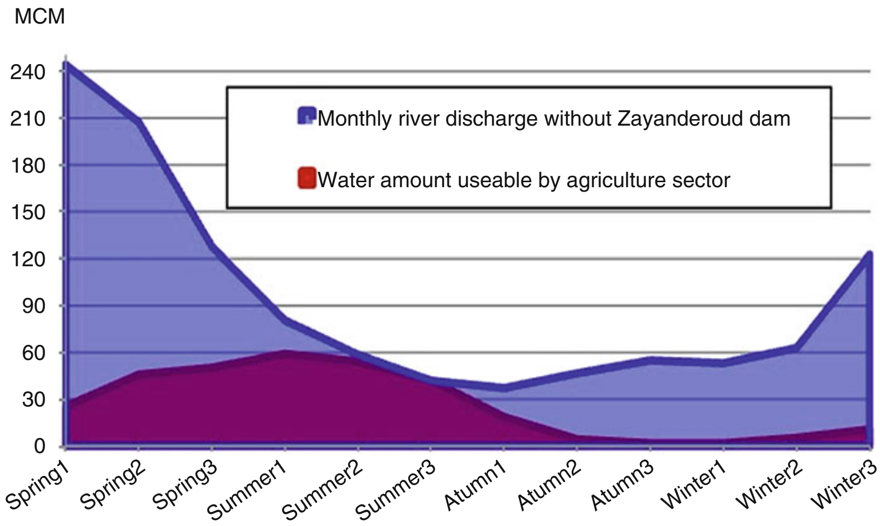

Fig. 5.2 Maximum operational water capacity in agricultural sector before the Zayandeh Rud dam construction (Zayandab Co. 2016)

further extractions from the Zayandeh Rud water resources on the other. These extractions will first damage the ecological rights of the river, Gavkhooni wetland, and the farmers from the around the river and most importantly will cause a continuous crisis in the basin.

Other outcomes of the Zayandeh Rud Dam construction are disruption of the natural regime of water flow in the river and expiration of traditional water distribution systems based on the natural water flow regime.

5.5 Historical Distribution Systems of the Zayandeh Rud River

Historical research indicates records of civilizations with 6000 years of Earthen Architecture in Roodasht close to Varzaneh on the west side of the Basin (Saiedi 2009), and the existence of the historical city of Isfahan during the Third Millennium BC. Formation of agricultural-based cities in a country with low rainfall with trust in the permanent flow of the river, which also provides drinking water, is not possible without a proper operational system (Hosseini Abari 2000).

The oldest water distribution system is a scroll attributed to Sheikh Baha'I (Iranian Minister and scientist, sixteenth century).

The Zayandeh Rud water distribution which is one of the most significant Iranian cultural heritages in water resource management and is traditionally known as Sheikh Baha'I Scroll is not an invention of a certain time or person, but it is a product of history, geography, tradition, social affairs, and religious beliefs of its residence in the past centuries. This distribution system has been altered over the centuries due to expansion or reduction of the drainage area and governmental decisions, some believe it to have a history close to 2000 years, and some believe it goes back to the Qajar or Safavid eras. The reason for each group lays in the content of historical texts, travelogues, and other sources. The overall result indicates the elegancy and accuracy of this country's ancestors in the management of the country's limited water resources (Hosseini Abari 2000).

The scroll did not originate from brilliant minds in a particular period. It is the product of historical evolution of this country's agricultural culture. What enhances the value of this scroll is the establishment of an exploitation system tested through time and completed throughout history. The last changes in this scroll go back to the Safavid era (sixteenth century). All beneficiaries of the Zayandeh Rud River Basin approve water distribution systems based on this scroll.

During the past decades, implementing interbasin transfers to and out of the Zayandeh Rud basin, more beneficiaries, and most importantly construction and operation of the Zayandeh Rud Dam has altered the overall operation system. The Zayandeh Rud Dam has altered the natural regime of the river by changing it to a regulated regime. According to the natural regime, the water distribution system for each sector is based on cultivation patterns and an irrigation calendar in each area.

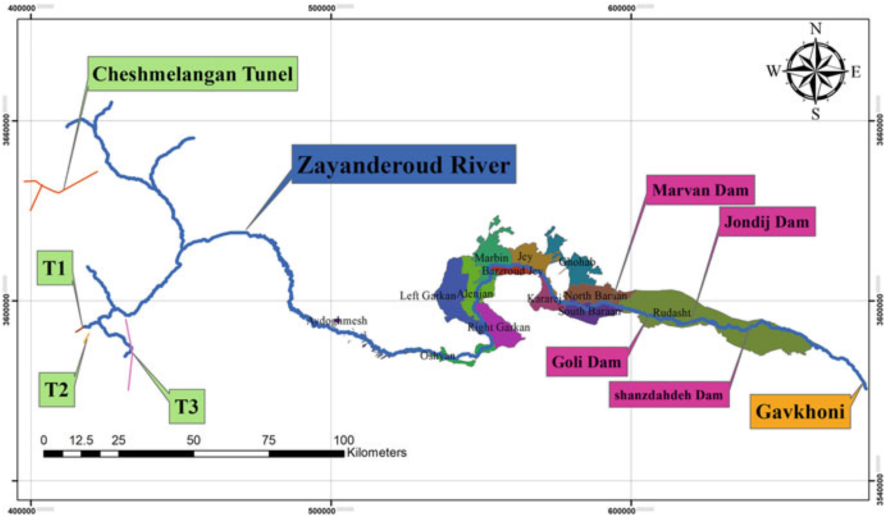

Fig. 5.3 Interbasin water transfer tunnels and Sheikh Baha'I scroll blocks locations

Based on the scroll within the 250 km of river course, the Zayandeh Rud runs through seven blocks covering hundreds of cities and villages including Isfahan metropolis. In this scroll, the Zayandeh Rud river's water is divided into 33 major contributions and during 165 days of the year (from June 2nd to November 16th) with water limitations, each contribution could use the water for 5 days, and during the remaining 200 days there would be no limitations (Zayandab Co. 2016).

Figure 5.3 shows the placing of blocks and also the interbasin water transfer tunnels to the Zayandeh Rud including Koohrang 1, 2, and 3 tunnels and the Cheshme Langan tunnel.

According to Fig. 5.3, the 7 blocks of Sheikh Baha'I scroll includes: Lenjan (including Ashian, left, and right Garkan), Alenajan, Marbin, Jey (including Jey, Barzroud, Ghohab), Kararej, Baraan (including northern and southern) and Roodasht.

Figure 5.4 indicates the irrigation sequence in a period of 165 days through the Zayandeh Rud blocks. As shown in the figure, Roodasht has access to the water in two 15-day rotations at the beginning and the end of the course.

The scroll is a reliable source for participating farmers with Haghabe (water right) in Zayandeh Rud River Management. According to Fig. 5.5, minor shareholders chose representatives called stream water masters for each village. These representatives were under the jurisdiction of the village elders and chose village headmen amongst themselves.

The village headmen chose one representative for each major share of that block. According to 33 major shares of the River, there were 33 representatives. The 33 major share representatives, who had the highest authority, chose one person to be in the highest rank of basin management called the headwater master for one year and introduce him/her to the government. The government then issued a government

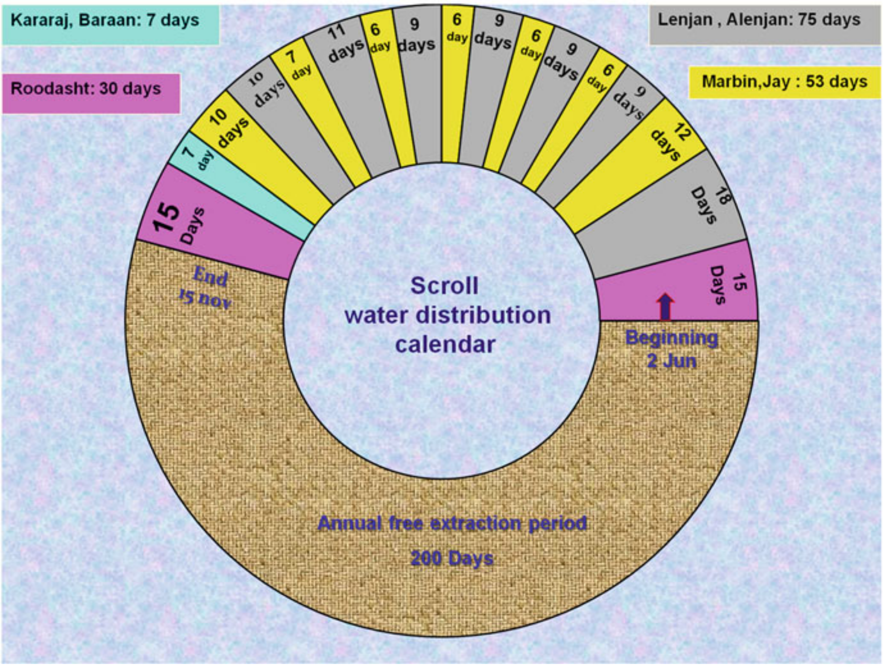

Fig. 5.4 Irrigation sequence in the scroll

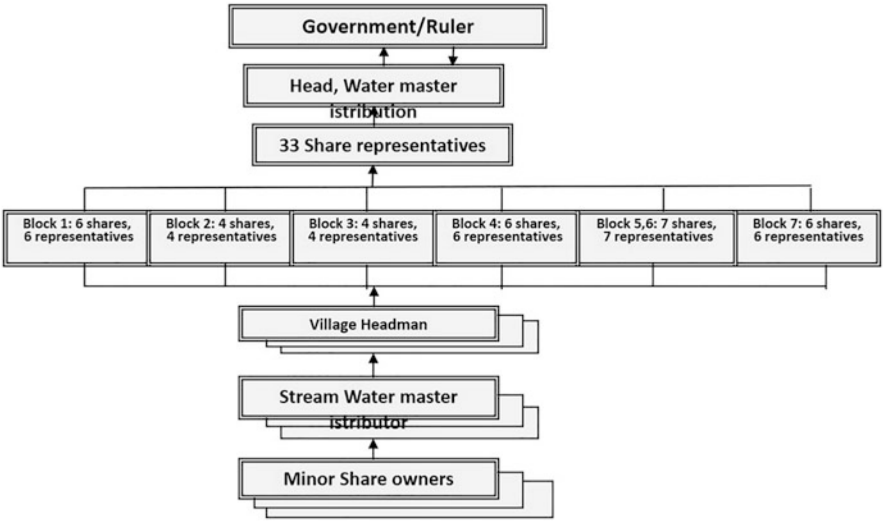

Fig. 5.5 Organizational chart of Zayandeh Rud utilization body elected by stakeholders

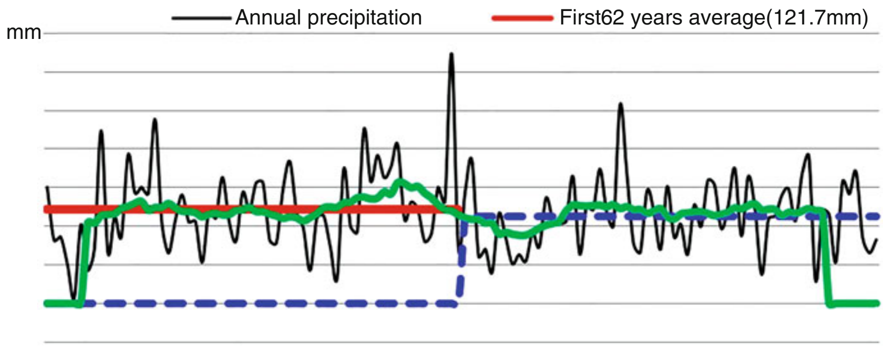

Fig. 5.6 Comparing first and second 62 years of 124 years precipitation rate in Isfahan city

order for this person and the representatives had the right to remove this person from the position. Based on the scroll 278 men were sent from the downstream blocks to the upstream blocks for supervision on river water disposal based on the scroll and its regulations.

Continuous water shortage crisis in the Zayandeh Rud river basin has been caused by climatic phenomenon or human factors. The Zayandeh Rud river basin has been struggling with continuous water shortage for the last two decades. Some consider drought and climate change to be the reason for this crisis. On the other hand, evidence shows human factors and inefficient water resource management to be the reason for the water shortage crisis. Although droughts play a major role in the expansion of the crisis, continuity of a crisis even during years with normal rainfall (years 2014 to 2016) confirms that human factors are the main reason for the water shortage crisis. To evaluate possible rainfall changes due to climate change, statistics for Isfahan's 124 rain years with the longest statistic period have been studied (Shafaghi 2002).

Figure 5.6 shows the annual precipitation curve and a 15-year moving average of annual and periodic change curve. Figure 5.6 compares average precipitation during the first 62 years of the statistical period (1894 to 1955) with average of the second half of the period (1956 to 2017). The average precipitation during the first 62 years is 121.7 mm and for the second 62 years, it is 112.8 mm, which indicates a 7% reduction in rainfall.

5.6 Routing Precipitation Changes in Mountainous Areas of Basin Upstream

Given that the major capacity of Zayandeh Rud irrigations is due to the amount of rainfall in the Zagros Mountain Range, therefore possible changes in precipitations in Chelgerd Station (indicator station located upstream of the basin) between 1957 and 2018 are shown in Fig. 5.6. Figure 5.7 shows the annual precipitation curve and moving average of annual and periodic change curve. According to Fig. 5.7, Chelgerd Station's average precipitation in the first half of the statistic period

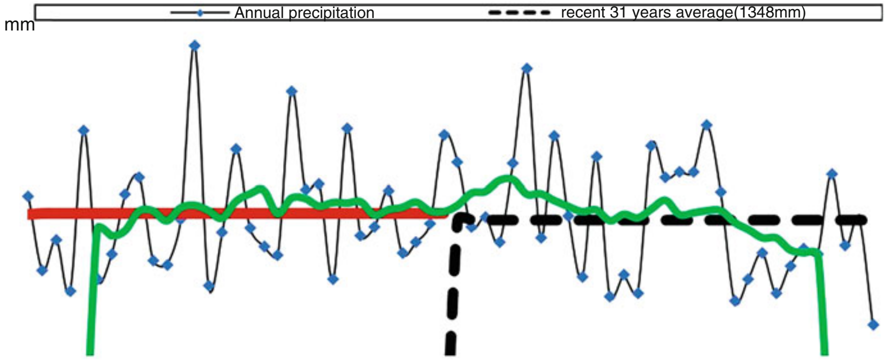

Fig. 5.7 Comparison of average precipitation between first 31 years and second 31 years of Chelgerd Indicator Station

(1957 to 1987) was 1386 mm and for the second half (1988–2018) 1348 mm. Average precipitation for the first 31 years compared to the second 31 years shows an approximate 3% reduction in rainfall.

5.7 Evaluating the Role of Climate Change in the Current Water Crisis in the Zayandeh Rud River Basin

Precipitation statistics in the central area (Isfahan City) and in mountainous areas and upstream of the catchment basin show decreased precipitation by 7% and 3%. In addition to rainfall reduction, climate change such as temperature increase and therefore more consumption has affected the Zayandeh Rud River Basin. Temperature increases lead to evaporation increases and therefore higher water consumption. Studies show that an increase in temperature by 0.63 to 1.13 degrees Celsius will cause evaporation and consumption increases of approximately 3.1–-4.8% (Zareian et al. 2016). Thus, the effects of climate change on the reduction of water irrigation in major mountainous areas (approximately 3%) and water consumption increase in the Zayandeh Rud River Basin (approximately 5%) giving a total of 8%, cannot be the reason for two decades of inclusive water crisis in the Zayandeh Rud River Basin.

5.8 Role of Human Factors in the Current Water Crisis

The Zayandeh Rud River Basin has been struggling with inclusive water shortage crisis for over two decades. Approximately 240 km of the Zayandeh Rud River is dry for several months in a year over successive years. The supply of the river and the wetland has been inadequate for nearly 14 years and the lack of water supply for

Table 5.4 Resources, costs, and water rights in the Zayandeh Rud River Basin (RBO-Zayandeh Rud 2014b)

	Resource name	Capacity (MCM)	Rightful owners	Capacity (MCM)
Water resources owned by shareholders	Natural Zayandeh Rud	845	River environment and wetland	176
	Koohrang First Tunnel	293	Drinking and industry before 1982	70.3
			Haghabe (water right) and Sahmabe (water portion)	419
			Isfahan water shareholders	655
Total of water resources owned by shareholders		1138	Total of legal shares	1320.3

Table 5.5 Water resources available to the government and government allocations and commitments

	Resource name	Capacity (MCM)	Government allocations and commitments	Capacity (MCM)
Water resources available to the government	Koohrang Second Tunnel	224	Isfahan Drinking water	370
			Allocated to Chaharmahal va Bakhtiari	237
			Kashan Drinking water	25
	Cheshme Langan Tunnel	130	Transfer to Yazd	56
			Industry	70
			Legal shares	300
Total water resources available to the government		354	Total government allocations	1058

farmers based on their Haghabe (water right), who have enjoyed this right for centuries, are a hallmark of the widespread water crisis in the Zayandeh Rud basin. This is not a temporary phenomenon caused by drought. It is a permanent crisis jeopardizing the central region of the country in environmental, social, and economic dimensions. During a normal year, the government only has the authority to transfer 354 MCM from second tunnels of Koohrang and Cheshmeh Langan. According to enactments by the River Basin Organization (RBO) of Zayandeh Rud (RBO-Zayandeh Rud 2014a) (mentioned in Tables 5.4 and 5.5 with some alterations), the basin is facing water shortage even during normal years with 7.4 MCM of rainfall.

Comparing the capacity of water resources available to the government (354 MCM in a normal year) with government allocations (1058 MCM) shows an extreme difference of 704 MCM in a year. Environmental legal shares from the River and Wetland have caused this capacity shortage. This situation has caused 240 km of dried river, 14 years of no water supply for the wetland, and depriving farmers of their legal share rights.

Table 5.5 indicates water resources capacity during years with average rainfall. During dry years, water shortage in the Zayandeh Rud River Basin is more than this amount and therefore its devastating consequences on the environment and agricultural sector will be far more severe.

5.9 Roodasht: A Historical Land Dependent on Water Flow in the Zayandeh Rud River

Roodasht is the last watering place of the Zayandeh Rud. A historical land with 43 cities and villages as well as a population of 50,000. The largest and most populated village in Roodasht are Varzaneh. Varzaneh is a historical city near the Gavkhooni Wetland and the last area with Haghabe (water right) in the Zayandeh Rud basin. Due to reduced rainfall and a lack of underground water resources, Roodasht is dependent on river water flow.

Roodasht's economy relies on agriculture and the Zayandeh Rud River is the only water resource for its farms. Roodasht is one of the Seven Blocks in Sheikh Baha'I Scroll and has 6 shares from 33 main irrigation shares of the natural river regime.

It is obvious that civilization relied on irrigated agriculture in Roodasht. This was possible only by a specific distribution system from the River. Four historical diversion dams in the Roodasht area including Bande Marvan, Bande Geli, Bande Jandij, and Band Shanzdah Deh distributed water through a network of traditional channels known as MADI (see Figs. 5.8, 5.9, 5.10 and 5.11). Construction of a diversion dam and modern irrigation network including the main and grade-2 channel network started in 1990. This network covered 42,000 hectares replacing the traditional network, which covered all villages and farms in Roodasht.

In recent years, due to water shortage caused by overcapacity water distribution and drought, supply of water for Roodasht's agriculture has been disturbed. Insufficient water supply to farmers over the past two decades and no water distribution from 2017 to 2019 has led to local farmers facing crises. Continuity of this situation may lead to group migrations and therefore empty cities and villages in the area, which will eventually destroy historical civilization centers in the area (Fig. 5.11).

Roodasht is surrounded by desert. According to studies, Roodasht has no underground water resources. The Roodasht surface aquifer is affected by the water flow from the river and agricultural irrigation. Due to salinity and soil alkalinity, the underground water quality is not high and therefore is used finitely with water from the river.

The secret to cities surviving and the desert not growing in thousands of years, is irrigated agriculture. Due to high water evaporation (approximately 2500 mm per year) and the low precipitation rate, without irrigation, agriculture in Roodasht is impossible. Due to a lack of underground water resources, water from the river is the only resource for agricultural water supply. Therefore, water supply for irrigation from the river is the farmer's lawful right, and is necessary for preventing increased

Fig. 5.8 Marvan Old Dam

Fig. 5.9 Goli Old Band

Fig. 5.10 Jondij Old Dam

Fig. 5.11 Shandzdah Deh Old Dam

desertification and protecting cities and villages in this area and Isfahan city and other central areas in the province.

Due to hardpan in Roodasht and the high evaporation rate, stopping agriculture and irrigation will cause salinity and soil alkalinity in the area (Zayandab Co. 1988). Naturally, salty and alkaline lands do not have the potential for creating vegetation and are exposed to severe wind erosion. The Gavkhooni wetland is also at risk of becoming a center of toxic poisoning, which is not only harmful to the historical city of Isfahan but also the entire Central Plateau of Iran and hundreds of cities and villages including the capital.

Irrigation water supply for cultivation of autumn crops based on crop patterns in Sheikh Baha'I scroll is the only way to save this historical area from desertification.

According to Sheikh Baha'I Scroll, Roodasht's traditional Haghabe (water share) is assigned to autumn cultivation. Based on the old and traditional water distribution system, Roodasht's water shares were determined in two periods. Fifteen days from the beginning to 15th of November each year for autumn cultivation and from June 4th to 18th of the next year supplying water for the final stages of autumn cultivation. Until construction of the reservoir dam on the river, water distribution would happen according to this system and, Roodasht would not receive water shares during summers.

Operating the reservoir dam in 1970 provided the possibility of delivering water to Roodasht during summers. Until 1994, water distribution in this area was done through traditional networks including four traditional diversion dams and the traditional channel networks. Due to salty and alkaline water pouring into the river, water in end dams has more salinity. Therefore, three different cultivation patterns are available in Roodasht. In upstream areas, receiving water from Marvan and Goli dams (first and second dams) products like cereal, alfalfa, sunflower, vegetables, and safflowers were cultivated. In the central area (Jondij Dam) vegetables, sunflowers, safflowers were not included in the cultivation pattern. At the end area of Roodasht (Shanzdah Deh Diversion Dam) in addition to cereals, instead of sunflower, vegetables, alfalfa, and safflower, salt-resistant products like cotton were cultivated. By exploiting the new irrigation system where four traditional diversion dams were replaced by the Rudashtain Diversion Dam, good quality of water was distributed among all agricultural lands and therefore no requirement for cultivating salinity resistant crops in the end areas of Roodasht existed.

5.10 Conclusion

The Zayandeh Rud River Basin has faced a severe water shortage for the past two decades. This crisis is not temporary nor completely caused by drought. It is a permanent crisis jeopardizing the central region of the country in environmental, social, and economic dimensions. Although drought plays a significant role, it is also caused by human factors and inefficient water resource management in the river basin. Roodasht being the last area of the Zayandeh Rud River Basin suffers the most from this water shortage crisis. Water supply for agricultural land irrigation from the river is the lawful right of the farmers and is also important for preventing increased desertification and protecting cities and villages in this area, the historical city of Isfahan and the Central Plateau of Iran.

A continuum of this situation may cause emigration from Roodasht cities and villages, which will lead to the destruction of historical civilization centers in this area. A threat with severe social outcomes and due to further desert growth will lead to severe environmental outcomes.

If the Gavkhooni wetland Haghabe (water right) is not provided, the wetland will be at risk of becoming the center of toxic poisoning with the transmission capacity of 1000 km, which is not only harmful to the historical city of Isfahan but also the entire Central Plateau of Iran and hundreds of cities and villages including the capital. Roodasht will be the first victim. Providing the environmental Haghabe and minimum water capacity for autumn cultivation based on the Sheikh Baha'l Scroll is the only way to save Roodasht from desertification. A greenhouse development program may solve employment problems for the farmers but it will not prevent desertification. This program will only be successful along with limited farming with the purpose of saving Roodasht from desertification.

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Chapter 6
Returning Periods of Drought and Climate Change in the Zayandeh Rud River Basin

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Contents

6.1 Introduction

Drought is the result of altered hydrological conditions, in particular, due to precipitation deficit over a period of time, and is one of the most common disasters in all kinds of climate regimes (Chen et al. 2013). Unlike other natural disasters, the effects

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of drought appear gradually over time, typically on the order of several months to several years. Drought analysis usually involves estimating one of the drought indices and then calculating drought characteristics based on the determined drought index such as severity, duration, and peak intensity (Yang 2010). Among the methods for determining drought characteristics, the threshold value could provide a frame of reference for drought assessment (Yevjevich 1967). As climate change is expected to vary worldwide due to natural and model ambiguities, predicting the impact of climate change on future droughts is vital for water resources management. In the Northern Hemisphere—between 15° and 45° latitudes, including the current study area—drought periods have been particularly severe (Mousavi 2005).

Several studies have investigated the impact of climate change on drought using various drought indices. For example, in many regions of the world, the Standardized Precipitation Index (SPI) and Reconnaissance Drought Index (RDI) have been used to analyze drought (Hoffman et al. 2009; Kirono et al. 2011; Lee et al. 2013; Selvaraju and Baas 2007; Serinaldi et al. 2009). For the watersheds in Iran, previous studies have used the Standardized Precipitation Index (SPI), Reconnaissance Drought Index (RDI), Percent of Normal Precipitation Index (PNPI), Agricultural Rainfall Index (ARI), and Multivariate Standardized Drought Index (MSDI) (Dastorani et al. 2011; Golian et al. 2015; Madadgar and Moradkhani 2011; Moradi et al. 2011; Sayari et al. 2013). The characterization of drought by severity and duration is widespread as these are interdependent parameters. In some cases, there is a high correlation between the duration of drought and its severity (Madadgar and Moradkhani 2011). Estimating drought return periods that are based solely on one of the drought characteristics, such as the duration or severity of drought, can be misleading as these features are correlated. As a case, finding the return periods of drought only based on the drought duration doesn't provide any information about other drought characteristics, namely, the severity of the drought or drought intensity. Hence, the severity of the drought may not be very severe on that duration, and the managers don't have to specifically plan for this drought, or it may be very severe so the water resources managers should plan for it earlier. Therefore, using a joint distribution function to study drought return periods might be beneficial. Copula is a model of multivariate distribution, which is becoming increasingly popular in hydrological studies (Chen et al. 2013; Madadgar and Moradkhani 2011; Serinaldi et al. 2009).

Even though there have been many studies regarding climate change and drought in Iran, little is known about the impact of climate change on drought characteristics in the Zayandeh Rud basin. This basin is one of the most complicated basins in Iran involving many problems with water recourses. In particular, there are limited studies that used bivariate and tri-variate joint functions to analyze spatial drought characteristics in a changing climate.

There are several agricultural areas in Isfahan province. Roodasht is one of the most important of these areas and is located in the eastern part of the Zayandeh Rud basin. The state of water resources affects agricultural activities and their products. It is very important to study the available water status, especially in the changing climate, in order to make proper decisions for the agricultural activities in the eastern part of the basin based on the water condition perspective in this part, in the future and under the climate change.

The main objectives of this study are the use of copula functions to estimate the drought frequencies, depicting the density contours of drought return period calculations based on tri-variate copula functions by considering climate change. Spatial maps of return periods of drought based on severity-duration-peak intensity tri-variate copula for the historical, the near future, and the far future periods in the basin are also illustrated. The procedure of this study consists of three main parts: (1) identifying the drought duration, severity, and peak intensity based on SPI, adapting various distribution functions to the drought characteristics, and finding one of the extreme historical drought occurrences and using appropriate fitted copulas to estimate frequency of this historically significant drought event, (2) quantification of the effects of climate change using the general circulation models (GCMs) for future periods, and (3) evaluation of future drought characteristics using selected copulas and calculation of the frequency of future drought events.

There are several parts in this article describing the copula's approach and implementation. Section 6.2 contains the methodology, including the description of the SPI drought index, the copula which is a multivariate probability distribution, the methods for calculating the return period based on copula, the climate scenarios, and the brief introduction of the study area as well as the methods used for collecting and analyzing the data. Section 6.3 contains the results and discussion of this research.

6.2 Methodology

6.2.1 Standardized Precipitation Index (SPI)

The Standardized Precipitation Index to estimate the meteorological drought was developed by McKee et al. (1993) and is calculated based on the precipitation data. The SPI value can be positive or negative, with positive values representing wet years and negative values dry years. Precipitation is the only parameter needed to calculate this index and therefore the calculation is relatively simple. The SPI index can also be calculated for several time scales (3, 6, 12, 24, and 48 months) and is helpful to assess droughts across various time resolutions. Each time scale indicates the effects of drought on different water resources. For example, one could look at a 1- or 2-month SPI for meteorological drought, anywhere from a 1-month to 6-month SPI for agricultural drought, and something like a 6-month up to 24-month SPI or more for hydrological drought analysis and applications (Svoboda et al. 2012). Some studies have used several SPI time scales to examine drought in different regions of the world (Golian et al. 2015; Madadgar and Moradkhani 2011; Moradi et al. 2011; Sayari et al. 2013). A 3-month SPI was selected in this study to better understand drought events. Fitting the gamma distribution to a climatological precipitation time series is appropriate according to Thom (1966). To calculate the SPI, the gamma

Table 6.1 SPI values

SPI value	Drought condition
2.0 and more	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
−0.99 to 0.99	Near normal
−1.0 to −1.49	Moderately dry
−1.5 to −1.99	Severely dry
−2 and less	Extremely dry

distribution function should first be adopted to the precipitation data. A cumulative probability distribution function used to calculate the SPI is shown in Eq. (6.1) as follows:

$$F(X) = \int_0^X f(X)dx = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^X X^{\widehat{\alpha-1}} e^{\frac{-X}{\beta}} dx \tag{6.1}$$

Finally, the result of Eq. (6.1) must converge with the standard normal cumulative distribution function, the mean of which is 0 and the standard division is equal to 1.

The severity of drought, the duration of the drought, and the peak intensity of the drought were calculated based on the theory of runs proposed by Yevjevich (1967). According to this method, the level of truncation for the drought investigation was set to −1 in order to take moderate and more severe dry conditions into account (Table 6.1). The drought duration is defined as successive months with an SPI value less than −1, the drought severity as an accumulative SPI value during the period with a successive SPI value less than −1, and the drought peak intensity as the minimum SPI value for every drought event.

The candidate distributions for drought characteristics were log-normal, exponential, gamma, and Weibull. Based on the Bayesian information criterion (BIC) method (Li et al. 2013), best-fitting distribution functions for severity, duration, and peak intensity were selected.

6.2.1.1 Historical Drought Analysis

The linear correlations between severity, duration, and peak intensity were calculated, and the correlation between each pair and almost all values are more than 0.5 (Fig. 6.1). The range of correlation values between drought severity and duration of the drought is between 0.5 and 0.7. The range of correlation values for severity and peak intensity of the drought were between 0.8 and 1. Furthermore, the correlation between the duration and peak intensity of the drought was between 0.4 and 0.7.

Based on recent studies to find the best distribution for drought characteristics (Shiau 2006; Xu et al. 2015), the exponential, gamma, log-normal, and Weibull distributions were selected to fit the duration, severity, and peak intensity of the drought. These distribution functions were fitted to the drought characteristics of the historical data. The maximum likelihood estimation (MLE) method was used to

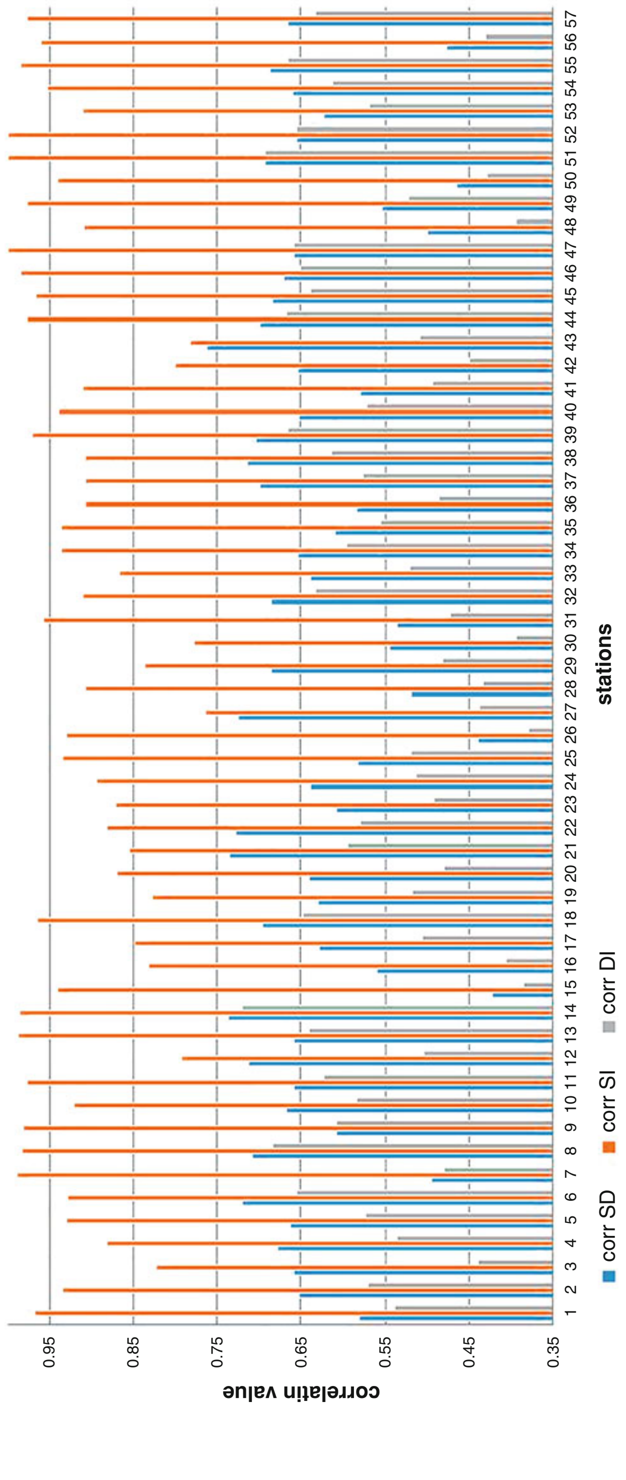

Fig. 6.1 Correlation between each pair of drought characteristics (*SD* severity-duration, *SI* severity-peak intensity, *DI* duration-peak intensity)

estimate the parameters of each distribution. For each station in the basin, the best-fitting distribution was selected. Moreover, the BIC method was used to select the best-fitting distribution for severity, duration, and peak intensity. Table 6.2 shows the BIC values for different distributions fitted to the drought characteristics in each station. Table 6.3 illustrates the number of stations with the marginal distribution which is best fitted for each drought characteristic, and Table 6.4 shows the final selected distributions. Selected distributions were used to derive severity, duration, and peak intensity for historical and future drought using GCM precipitation projections.

6.2.2 Copula-Based Multivariate Probability Distribution

Copula is the joint multivariate distribution function used to couple the different probability distribution functions. Concerning a random vector of $(x_1, x_2, \ldots, x_n)$ with the cumulative marginal distribution functions $F_i(x) = P[X_i \leq x]$ which are continuous. There are uniform marginals for each element of random vectoring, as follows:

$$(U_1, U_2, \ldots, U_d) = (F_1(X_1), F_2(X_2), \ldots, F_d(X_d)) \tag{6.2}$$

So, copula function can determine the joint distribution function of $(U_1, U_2, \ldots, U_d)$ for the vector of $(x_1, x_2, \ldots, x_n)$:

$$C(U_1, U_2, \ldots, U_d) = P[U_1 \leq u_1, U_2 \leq u_2, \ldots, U_d \leq u_d] \tag{6.3}$$

This equation can be representative of:

$$C(U_1, U_2, \ldots, U_d) = P\left[X_1 \leq F_1^{-1}(u_1), X_2 \leq F_2^{-1}(u_2), \ldots, X_d \leq F_d^{-1}(u_d)\right] \tag{6.4}$$

Scaler theory (1959) shows that for every n-dimensional cumulative distribution function (H) with its marginal varieties $F_1, \ldots, F_n$, copula function C can be defined as:

$$\begin{aligned} H(X_1, X_2, \ldots, X_n) &= C[F_1(X_1), F_2(X_2), \ldots, F_n(X_n)] \\ &= C(U_1, U_2, \ldots, U_n) \end{aligned} \tag{6.5}$$

where $u_1, \ldots, u_n$ are distribution functions of $X_1, \ldots, X_n$ (Nelsen 2007).

Copula distribution functions can build the joint distributions from two or more marginal distributions while maintaining the statistical properties of their original distributions. Marginal distributions must be uniform, in the range of (0, 1). Copula functions are categorized into different families and some of them were widely used in hydrology studies (Yan 2007). Normal copula and *t* copula in elliptical copula

Table 6.2 BIC values for different distributions fitted to drought characteristics in each station

Station	Duration				Severity				Peak intensity			
	Exponential	Gamma	Log-normal	Weibull	Exponential	Gamma	Log-normal	Weibull	Exponential	Gamma	Log-normal	Weibull
1	61.60	61.02	55.15	58.97	48.71	40.96	35.97	38.83	35.97	38.83	38.83	35.97
2	16.80	16.80	16.87	16.87	14.44	14.44	14.44	16.80	14.44	14.44	16.80	14.44
3	12.51	12.51	12.78	12.78	11.03	11.03	11.03	12.51	11.34	11.86	12.51	11.03
4	11.03	9.15	9.15	11.03	9.15	8.52	8.52	8.52	11.03	9.15	9.15	11.03
5	11.03	9.15	9.15	11.03	9.15	8.52	8.52	8.52	11.03	9.15	9.15	11.03
6	11.03	9.15	9.15	11.03	9.15	8.52	8.52	8.52	11.03	9.15	9.15	11.03
7	11.03	9.15	9.15	11.03	9.15	8.52	8.52	8.52	11.03	9.15	9.15	11.03
8	11.03	9.15	9.15	11.03	9.15	8.52	8.52	8.52	11.03	9.15	9.15	11.03
9	11.03	9.15	9.15	11.03	9.15	8.52	8.52	8.52	11.03	9.15	9.15	10.87
10	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.87
11	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.87
12	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.87
13	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.87
14	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.87
15	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.87
16	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.87
17	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.87
18	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.87
19	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.87
20	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.87
21	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.87
22	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.87
23	10.87	9.15	9.15	10.87	9.15	8.52	8.52	8.52	10.87	9.15	9.15	10.46

(continued)

Table 6.2 (continued)

Station	Duration				Severity				Peak intensity			
	Exponential	Gamma	Log-normal	Weibull	Exponential	Gamma	Log-normal	Weibull	Exponential	Gamma	Log-normal	Weibull
24	10.46	9.15	9.15	10.46	9.15	8.52	8.52	8.52	10.46	9.15	9.15	10.46
25	10.46	9.15	9.15	10.46	9.15	8.52	8.52	8.52	10.46	9.15	9.15	10.46
26	10.46	9.15	9.15	10.46	9.15	8.52	8.52	8.52	10.46	9.15	9.15	10.46
27	10.46	9.15	9.15	10.46	9.15	8.52	8.52	8.52	10.46	9.15	9.15	10.46
28	10.46	9.15	9.15	10.46	9.15	8.52	8.52	8.52	10.46	9.15	9.15	10.46
29	10.46	9.15	9.15	10.46	9.15	8.52	8.52	8.52	10.46	9.15	9.15	10.46
30	10.46	9.15	9.15	10.46	9.15	8.52	8.52	8.52	10.46	9.15	9.15	10.46
31	10.46	9.15	9.15	10.46	9.15	8.52	8.52	8.52	10.46	9.15	9.15	10.46
32	10.46	9.15	9.15	10.46	9.15	8.52	8.52	8.52	10.46	9.15	9.15	10.46
33	10.46	9.15	9.15	10.46	9.15	8.52	8.52	8.52	10.46	9.15	9.15	10.46
34	10.46	9.15	9.15	10.46	9.15	8.52	8.52	8.52	10.46	9.15	9.15	10.46
35	10.46	9.15	9.15	10.46	9.15	8.52	8.52	8.52	10.46	9.15	9.15	10.46
36	10.46	9.15	9.15	10.46	9.15	8.52	8.52	8.52	10.46	9.15	9.15	9.15
37	9.15	8.97	8.97	9.15	8.97	8.52	8.52	8.52	9.15	8.97	8.97	9.15
38	9.15	8.97	8.97	9.15	8.97	8.52	8.52	8.52	9.15	8.97	8.97	9.15
39	9.15	8.97	8.97	9.15	8.97	8.52	8.52	8.52	9.15	8.97	8.97	9.15
40	9.15	8.97	8.97	9.15	8.97	8.52	8.52	8.52	9.15	8.97	8.97	9.15
41	9.15	8.97	8.97	9.15	8.97	8.52	8.52	8.52	9.15	8.97	8.97	9.15
42	9.15	8.97	8.97	9.15	8.97	8.52	8.52	8.52	9.15	8.97	8.97	9.15
43	9.15	8.97	8.97	9.15	8.97	8.52	8.52	8.52	9.15	8.97	8.97	9.15
44	9.15	8.97	8.97	9.15	8.97	8.52	8.52	8.52	9.15	8.97	8.97	9.15
45	9.15	8.97	8.97	9.15	8.97	8.52	8.52	8.52	9.15	8.97	8.97	9.15
46	9.15	8.97	8.97	9.15	8.97	8.52	8.52	8.52	9.15	8.97	8.97	9.05
47	9.05	8.97	8.97	9.05	8.97	8.52	8.52	8.52	9.05	8.97	8.97	9.05

48	9.05	8.97	8.97	9.05	8.97	8.52	8.52	8.52	9.05	8.97	8.97	9.05
49	9.05	8.97	8.97	9.05	8.97	8.52	8.52	8.52	9.05	8.97	8.97	9.05
50	9.05	8.97	8.97	9.05	8.97	8.52	8.52	8.52	9.05	8.97	8.97	9.05
51	9.05	8.97	8.97	9.05	8.97	8.52	8.52	8.52	9.05	8.97	8.97	9.05
52	9.05	8.97	8.97	9.05	8.97	8.52	8.52	8.52	9.05	8.97	8.97	9.05
53	9.05	8.97	8.97	9.05	8.97	8.52	8.52	8.52	9.05	8.97	8.97	9.05
54	9.05	8.97	8.97	9.05	8.97	8.52	8.52	8.52	9.05	8.97	8.97	9.05
55	9.05	8.97	8.97	9.05	8.97	8.52	8.52	8.52	9.05	8.97	8.97	9.05
56	9.05	8.97	8.97	9.05	8.97	8.52	8.52	8.52	9.05	8.97	8.97	9.05
57	9.05	8.97	8.97	9.05	8.97	8.52	8.52	8.52	9.05	8.97	8.97	9.05

Table 6.3 The number of stations that has the best fitted of defined distribution for each drought characteristic

Drought characteristic	Exponential	Gamma	Log-normal	Weibull
Severity	6	1	41	9
Duration	0	0	57	0
Intensity	52	0	3	2

Table 6.4 Selected distribution for each drought characteristic

Drought characteristic	Selected distribution
Severity	Log-normal
Duration	Log-normal
Intensity	Exponential

family and Gumbel, Frank, and Clayton copula in the Archimedean copula family are commonly used copula functions families in hydrology and are used in this study as well. Table 6.5 shows the specifications of these copula functions.

6.2.2.1 Using Copula

Drought is an event with several characteristics such as drought duration, severity, and peak intensity. These characteristics are not independent and are related to each other. Because of the high correlation between each pair of drought characteristics, namely, severity vs. duration, severity vs. peak intensity, and duration vs. peak intensity, it is essential to use joint distribution functions in drought analysis. Thereupon analyzing the drought based only on one of its characteristics can lead to misinterpreting the drought event. To explain more, by calculating the return period solely based on one of the drought characteristics, the results don't imply any information about other characteristics. So the water managers don't have enough information for making decisions about the basin. Using copula functions, it is possible to calculate the return period of the specific drought event with distinct characteristics. These advantages were the motivation of using copula functions as the joint distribution function in this research.

Based on Chen et al. (2013), three common copulas in the Archimedean family (Clayton, Frank, and Gumbel-Hougaard) and two common copulas in the meta-elliptical family (*t* and normal) were used for constructing tri-variate joint distribution. Best-fitting copula was chosen using the BIC method for each station in the basin. Table 6.6 shows the BIC value for different tri-variate copula distribution in each station. Table 6.7 illustrates the number of stations with the best-fitting copula for each cupola function, and Table 6.8 shows the resultant copula for each pair. The best-fitting copulas for each pair of the characteristics (severity vs. duration, severity vs. peak intensity, and duration vs. peak intensity) were used for the historical and the future assessment of drought.

Table 6.5 Properties of used copula functions in this study

Copula type	Function	Relationship between parameters
Clayton	$C(u,v) = (u^{-\theta} + v^{-\theta} - 1)^{-1/\theta}$	$\tau^* = \frac{\theta}{2+\theta}, \theta \in [1, \infty)$
Gumbel-Hougaard	$C(u,v) = \exp\{-[(-\ln u)^{\theta} + (-\ln v)^{\theta}]^{1/\theta}\}$	$\tau^* = 1 - \frac{1}{\theta}, \theta \in (0, \infty)$
Frank	$C(u,v) = -\frac{1}{\theta} \ln \left[1 + \frac{(e^{\theta u}-1)(e^{-\theta v}-1)}{e^{-\theta}-1}\right]$	$\tau^* = 1 + \frac{4}{\theta}\left[\frac{1}{\theta}\int_0^{\theta} \frac{t}{e^t-1}\, dt - 1\right], \theta \in R$
Normal	$C(u,v) = \int\limits_{-\infty}^{\varnothing^{-1}(u)} \int\limits_{-\infty}^{\varnothing^{-1}(v)} \frac{1}{2\pi(1-\rho^2)^{\frac{1}{2}}} \exp\left\{-\frac{x^2-2\rho xy+y^2}{2(1-\rho^2)}\right\} dxdy$	$\rho(X,Y) = \sin\left(\frac{\pi}{2}\tau\right)$
t	$C(u,v) = \int\limits_{-\infty}^{t_v^{-1}(u)} \int\limits_{-\infty}^{t_v^{-1}(v)} \frac{1}{2\pi(1-\rho^2)^{\frac{1}{2}}} \exp\left\{1 + \frac{x^2-2\rho xy+y^2}{v(1-\rho^2)}\right\}^{-(v+2)/2}$	$\rho(X,Y) = \sin\left(\frac{\pi}{2}\tau\right)$

*τ denotes Kendall's tau, which is used to measure and test the dependence

Table 6.6 BIC value for different tri-variate copula distributions in each station

Station	*t*	Gaussian	Gumbel	Frank	Clayton
1	−57.93	−42.47	−51.91	−43.98	−31.26
2	−48.00	4.12	−52.86	−46.69	−30.31
3	−111.00	−113.78	−53.03	−49.01	−43.01
4	−37.22	1.43	−42.48	−36.17	−24.11
5	−58.04	−40.79	−51.72	−44.19	−34.82
6	−72.33	−62.97	−57.02	−48.91	−43.32
7	−74.93	−74.02	−49.67	−44.51	−46.69
8	−98.77	−98.55	−52.72	−48.45	−49.71
9	−49.27	−37.42	−50.50	−48.78	−28.86
10	−41.64	−31.23	−37.93	−29.22	−21.77
11	−69.58	−66.90	−44.63	−32.06	−30.02
12	−55.98	−55.34	−43.13	−31.59	−30.53
13	−99.23	−101.18	−51.37	−40.74	−43.16
14	−104.35	−103.57	−56.86	−48.91	−45.78
15	−119.99	−122.94	−54.38	−51.91	−54.33
16	−107.94	−110.77	−47.04	−46.18	−42.14
17	−89.98	−90.69	−64.32	−58.27	−45.31
18	−78.95	−81.83	−44.76	−37.59	−29.40
19	−33.28	−0.19	−28.23	−27.05	−23.76
20	−52.45	−55.28	−31.50	−26.63	−25.51
21	−50.55	−51.23	−37.35	−28.15	−19.62
22	−61.79	−64.57	−37.30	−24.85	−23.81
23	−57.16	−59.37	−49.73	−37.44	−30.65
24	−50.55	−50.70	−47.27	−37.15	−26.19
25	−77.39	−79.58	−53.18	−48.94	−40.63
26	−67.10	−48.97	−41.71	−41.59	−39.02
27	−86.93	−86.93	−39.76	−35.04	−29.56
28	−57.49	−53.25	−40.29	−43.83	−13.21
29	−74.01	−76.36	−42.07	−38.86	−29.11
30	−72.68	−75.57	−36.74	−31.73	−28.08
31	−34.34	−0.39	−32.45	−33.73	−28.96
32	−59.08	−61.88	−32.56	−30.61	−33.41
33	−40.96	−39.08	−31.39	−23.41	−17.13
34	−60.46	−63.26	−40.99	−30.26	−26.83
35	−69.44	−72.28	−53.64	−41.06	−37.28
36	−77.17	−80.10	−52.75	−39.93	−32.52
37	−48.70	−46.20	−35.92	−31.41	−28.97
38	−71.10	−71.48	−46.31	−43.27	−35.77
39	−57.65	−49.58	−48.45	−47.25	−37.80
40	−63.08	−65.92	−30.10	−26.91	−26.60
41	−71.30	−73.09	−38.29	−35.23	−24.71
42	−33.77	13.20	−31.48	−33.19	−29.53

(continued)

Table 6.6 (continued)

Station	*t*	Gaussian	Gumbel	Frank	Clayton
43	−35.59	78.74	−35.49	−33.30	−26.98
44	−42.25	−43.46	−36.17	−27.54	−22.87
45	−48.94	−29.26	−48.39	−40.74	−17.05
46	−54.90	−19.34	−55.46	−49.03	−15.70
47	−63.99	−66.91	−40.32	−30.33	−21.65
48	−63.64	−65.53	−45.49	−46.54	−24.65
49	−70.63	−72.77	−35.07	−36.67	−37.80
50	−63.39	−63.93	−42.37	−40.92	−36.01
51	−76.68	−79.63	−35.41	−31.65	−33.82
52	−69.47	−72.33	−35.69	−27.44	−24.05
53	−61.55	−64.44	−33.38	−34.59	−21.45
54	−65.43	−68.32	−35.60	−37.62	−26.12
55	−61.82	−57.40	−36.36	−36.57	−31.16
56	−70.22	−72.21	−37.19	−40.12	−36.83
57	−77.90	−80.78	−40.73	−44.84	−32.85

Table 6.7 Number of stations with the best-fitted copula for each copula function

Copula	*t*	Normal	Gumbel	Frank	Clayton
Copula severity-duration	0	6	48	3	0
Copula severity-intensity	0	25	8	13	11
Copula duration-intensity	0	21	29	6	1
Copula severity-duration-intensity	21	32	4	0	0

Table 6.8 Selected copula

Marginal of copula	Selected copulab
Severity- duration	Gumbel
Severity- intensity	Normal
Duration- intensity	Gumbel
Severity-duration-intensity	Normal

6.2.3 Return Periods Based on Copula

Understanding the frequency of extreme events is of significant importance in hydrologic studies. For the assessment of drought, the time between the beginning of a drought event and the beginning of the next drought event is defined as the interarrival time, and the mean interarrival time between occurrences of drought events is defined as a return period (Serinaldi et al. 2009).

The equation for calculating the return period of a multivariate approach is developed based on the univariate return period method. According to Shiau (2006), the calculation of a joint return period can be done using two logical operators: *and* and *or* joint return periods. The *and* operator represents the return period which includes all the variables being greater than or equal to the given values, and *or* operator represents that at least one variable is greater than or equal to the given values.

The equations to calculate the tri-variate return periods for d $D \geq d$ and $S \geq s$ and $I \geq i$ and for $D \geq d$ or $S \geq s$ or $I \geq i$ are as follows:

$$T_{and} = \frac{E(L)}{1 - P(D \geq d, S \geq s, I \geq i)}$$
$$= \frac{E(L)}{1 - F_D(d) - F_S(s) - F_I(i) + C[F_D(d), F_S(s)]}$$
$$+C[F_D(d), F_I(i)] + C[F_S(s), F_I(i)] - C[F_D(d), F_S(s), F_I(i)] \quad (6.6)$$

$$T_{or} = \frac{E(L)}{1 - P(D \geq d \; or \; S \geq s \; or \; I \geq i)} = \frac{E(L)}{1 - C[F_D(d), F_S(s), F_I(i)]} \quad (6.7)$$

where T_d is the drought return period, $E(L)$ is the expected drought interval time, D represents drought duration, S is drought severity, and I is peak intensity of drought.

The return period of an event with drought duration, drought severity, and drought intensity, more than the specific value, denotes a more severe drought event. Hence, T_{and} was considered in this study to calculate.

6.2.4 Climate Scenarios

A changing climate in the future takes into account several factors, such as the projected greenhouse gas emissions, development in the technology, changes in energy generation and land use, the regional economic circumstances, and the population growth. Several research groups worked on this issue under the supervision of the intergovernmental panel on climate change (IPCC). In the years 2013 to 2014, the fifth assessment report (AR5) was published based on the new set of scenarios, called Representative Concentration Pathways (RCPs), which describes an emission trajectory and concentration up to the year 2100 and consequent forcing (Wayne 2013).

The NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset was available at 0.25° resolution (Thrasher et al. 2013). For this study, daily precipitation data were downloaded for both the historical period of 30 years between 1979 and 2008 and the future periods of 84 years between 2016 and 2099 from 15 different GCMs for 2 different scenarios: RCP4.5 and RCP 8.5 (Table 6.9). These scenarios are representative of stabilized total radiated forcing and high greenhouse gas concentration levels, respectively.

Table 6.9 Features of the used GCM models

(1) Model name (2) Vintage	(1) Institution (2) Main reference(s)
(1) BNU-ESM (2) 2011	(1) Beijing Normal University (2) Ji et al. (2014)
(1) CanESM2 (2) 2010	(1) Canadian Center for Climate Modelling and Analysis (2) Arora et al. (2011), von Salzen et al. (2013)
(1) CCSM4 (2) 2010	(1) US National Centre for Atmospheric Research (2) Gent et al. (2011)
(1) CESM1(BGC) (2) 2010	(1) NSF-DOE-NCAR (2) Long et al. (2012), Hurrell et al. (2013)
(1) CNRM-CM51 (2) 2010	(1) Centre National de Recherches Meteorologiques and Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique (2) Voldoire et al. (2013)
(1) CSIRO-Mk3.6.0 (2) 2009	(1) Queensland Climate Change Centre of Excellence and Commonwealth Scientific and Industrial Research Organisation (2) Rotstayn et al. (2012)
(1) GFDL-ESM2M (2) 2011	(1) NOAA Geophysical Fluid Dynamics Laboratory (2) Dunne et al. (2012, 2013)
(1) IPSL-CM5A-LR (2) 2010	(1) Institut Pierre Simon Laplace (2) Dufresne et al. (2012)
(1) IPSL-CM5A-MR (2) 2009	(1) Institute Pierre Simon Laplace (2) Dufresne et al. (2012)
(1) MIROC-ESM-CHEM (2) 2010	(1) University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (2) Watanabe et al. (2011)
(1) MPI-ESM-LR (2) 2009	(1) Max Planck Institute for Meteorology (2) Giorgetta et al. (2013)
(1) MPI-ESM-MR (2) 2009	(1) Max Planck Institute for Meteorology (2) Giorgetta et al. (2013)
(1) MRI-CGCM3 (2) 2011	(1) Meteorological Research Institute (2) Yukimoto et al. (2011, 2012)
(1) NorESM1-M (2) 2011	(1) Norwegian Climate Centre (2) Iversen et al. (2013)
(1) INM-CM4 (2) 2009	(1) Russian Institute for Numerical Mathematics (2) Volodin et al. (2010)

6.2.5 *Study Area*

The Zayandeh Rud basin is located in Isfahan province in the central part of Iran (Fig. 6.2). This basin covers an area of 28,000 km^2 between 31°–34° north latitude and 49°–53° east longitude, and it is a part of the central desert of Iran. It is limited by the Salt Lake basin in the north and the Karoon basin and the Dez basin in the west and southwest. Also, it is confined by the Deghsorkh and Siahkoh Desert basins in the east and the Shahreza basin in the south. The Zayandeh Rud river, which originates from the Zagros Mountains in the west of Iran, flows through the basin

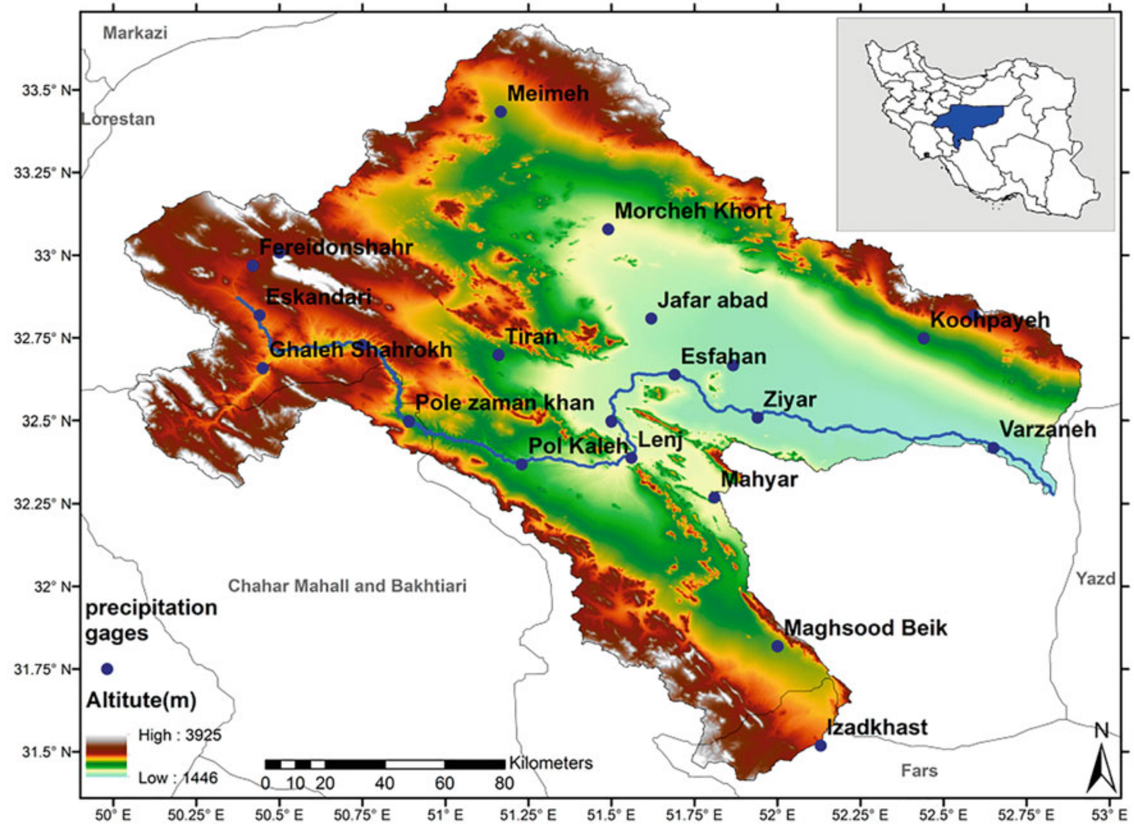

Fig. 6.2 Geographic location of the Esfahan province, the SRTM 90 m DEM map of the study area, and the spatial distribution of the used precipitation gauges

and drains into the Gavkhuni swamp located in the southeast of Isfahan province. Altitude in the basin is varied and changes from 1446 to 3925 m which is responsible for diverse climate regimes in the region. The average annual precipitation is about 211 mm in the basin, but it exhibits a high level of spatial variability. The northern and high altitude areas receive an annual precipitation of about 300–1345 mm, while the central and eastern parts of the basin including the Roodasht area receive about 75–230 mm per year. Most of the precipitation occurs in the winter months from December to April.

Safavi et al. (2014) reported that the basin experienced 11 dry years, 4 normal years, and 6 wet years during the period between 1991 and 2011. A study by Gohari et al. (2013) analyzed the impact of climate change on agricultural production and water use efficiency from 2015 to 2044 in the Zayandeh Rud basin using GCM models extracting from AR4 and discussed the reduction in annual precipitation from 11 to 31% as well as the variability in the monthly precipitation.

Since there are lots of large industries and agricultural areas located in the basin, and there are some water extractions to transfer water to neighboring cities, this basin is one of the most complex and important basins in Iran. Looking at the recent trend of a reduction in precipitation and the lack of water in the river during several months in the year, estimating the frequency of possible future droughts and their characteristics and the impact of climate change on future droughts is of significant importance for water resources management. Despite this importance, there are not enough future drought studies for the basin which contemplate all aspects of drought characteristics.

6.2.6 Data

6.2.6.1 Observed Data

For the current study, precipitation data of the stations were obtained from the Iran meteorological organization. Although the basin has more than 30 years of data for different stations, it was very difficult to find the period for which all the stations' data cover that same period. In some stations, there were even more than 50 years of data; however, some years' data are missing. Also, the literature review mentions that 30 years' data are sufficient to estimate the drought. Among the stations, 22 rain gauge stations were selected with daily data from 1979 to 2008. This period was the best period with the best coverage and overlap during the period. These stations were evenly distributed in the basin. Two specific stations were selected from these stations in order to have a better understanding of the precipitation patterns that represented two distinct regions within the basin. One of the stations was located upstream and another one downstream of the basin, near the Roodasht area. Figure 6.3 shows the change in monthly precipitation climatology for each station. As shown in Fig. 6.3, the precipitation upstream was higher than at the downstream station. In addition, it is clear that the variance of precipitation in the upstream station

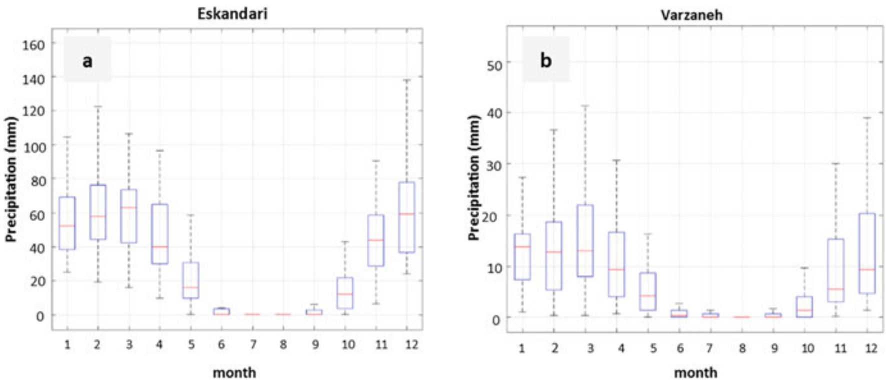

Fig. 6.3 Change in monthly precipitation during the past period (1979–2008): (**a**) Eskandari located in the upper part, (**b**) Varzaneh located in the downstream

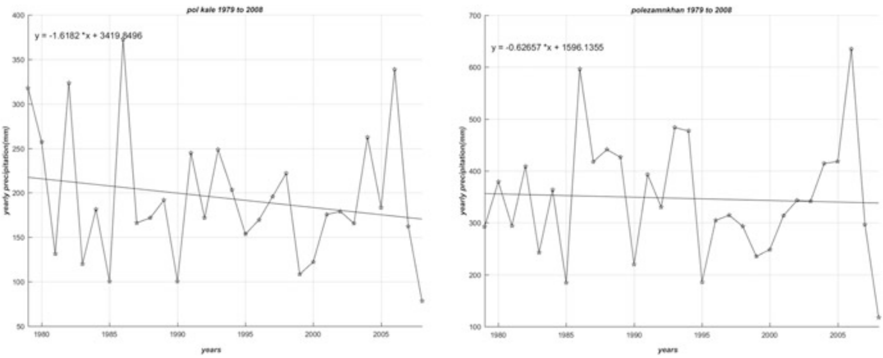

Fig. 6.4 Trend of precipitation during 30 years (1979–2008) in two stations located in the upstream of the basin

was lower than the downstream station. The precipitation trends of the entire 22 stations were evaluated by plotting the amount of precipitation over the past 30 years. For instance, Figs. 6.4 and 6.5 show the decreasing trends in precipitation from two stations upstream and downstream of the basin. As shown, the downward trend is more significant in the upstream stations compared to the downstream stations.

6.2.6.2 Data Analysis

A visual display of the result on the map can be helpful for understanding the conditions in the basin better. Using this kind of map, it is easier to peruse the general situation of each part in the basin and recognize the most critical parts. Hence, decision-makers can manage the water resources based on the general map of

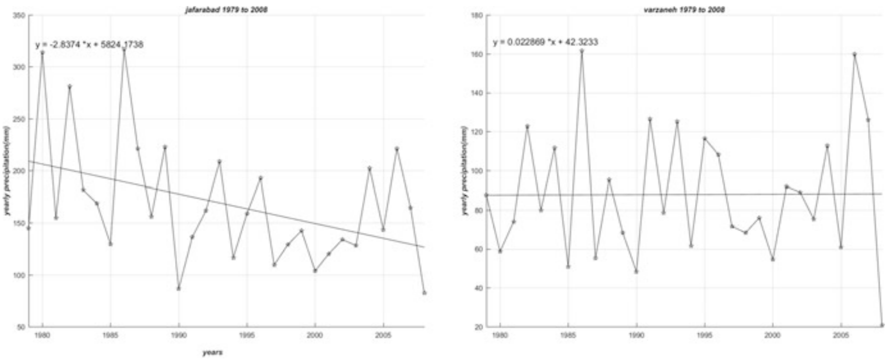

Fig. 6.5 Trend of precipitation during 30 years (1979–2008) in two stations located in the downstream of the basin

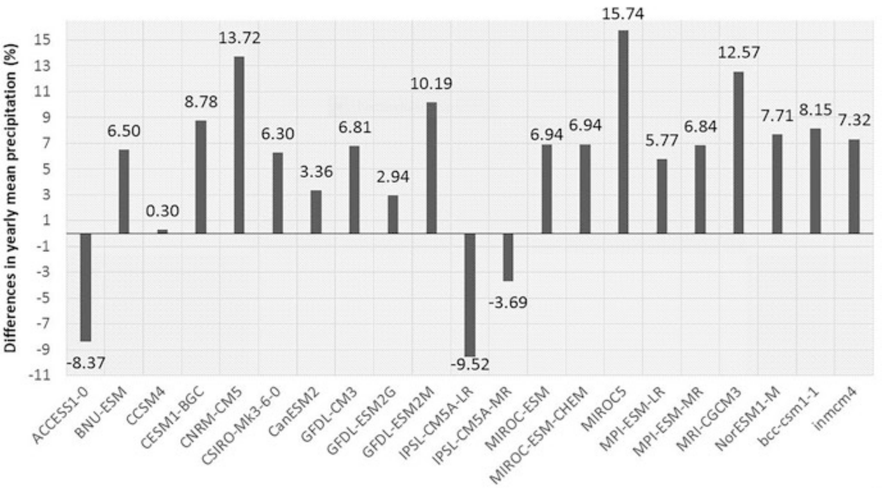

Fig. 6.6 Yearly mean precipitation differences of GCM models data with observation data in the basin (%)

the conditions in the catchment. Earlier literature has rarely used this method of illustration of their results. Since it was recognized that 22 stations within the basin might be insufficient for spatial analysis, this study used the NEX-GDDP historical data available for the 57 grids in the basin. Thus, after analyzing and comparing the observation data and the downloaded data, the gridded downloaded data from 15 GCMs available from NEX-GDDP historical scenario simulations was used for the spatial analysis. In order to verify the accuracy of GCM data, the station-observed data was compared with the GCM data. As illustrated in Fig. 6.6, the CCSM4 model has the lowest amount of percentile differences from observed

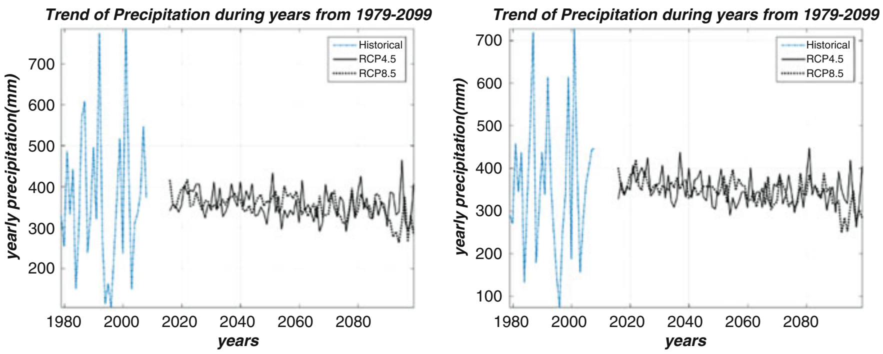

Fig. 6.7 Trend of precipitation in the future in comparison to the past in two stations located in the upper portion of the basin

data. Hence, CCSM4 data was selected for additional analysis to develop gridded data.

The available gridded data from 15 GCMs for the future was downloaded from NEX-GDDP future scenarios simulation. Annual precipitation was calculated using this downloaded data. Then the average of 15 GCM models was computed under RCP4.5 and RCP8.5 separately in each grid to evaluate the trend in precipitation. Figure 6.7 shows the trend in precipitation for selected grids located in the upper portion of the basin, and Fig. 6.8 shows this trend for a few selected grids located in the central and eastern portion of the basin including Roodasht. From these figures, it was apparent a significant decreasing precipitation trend can be expected in the upper regions of the basin in the future. Unlike the upper portion, there was no remarkable trend in the central and eastern sections of the basin.

6.3 Results and Discussion

As already mentioned, the lack of rainfall leads to drought and can negatively impact on available water resources in the basin. The effects of climate change on the amount of rainfall and other its effects also differ in various basins. As the water resources in the basin decrease, agricultural activities become limited. Roodasht is one of the most important agricultural areas in the eastern part of the basin. It is therefore very important to investigate the impact of climate change on the rainfall trend and also drought conditions in the basin, especially in the Roodasht area. In this study, the duration, severity, and peak intensity of the drought were calculated based on the SPI values for the historical period (1979–2008) in the basin, and then various distribution functions were fitted to these drought characteristics. Then one of the extreme historical drought events was selected as the benchmark for comparing future drought conditions and past situations. For this reason, the 90th percentile of drought severity, duration, and peak intensity of drought events in the historical

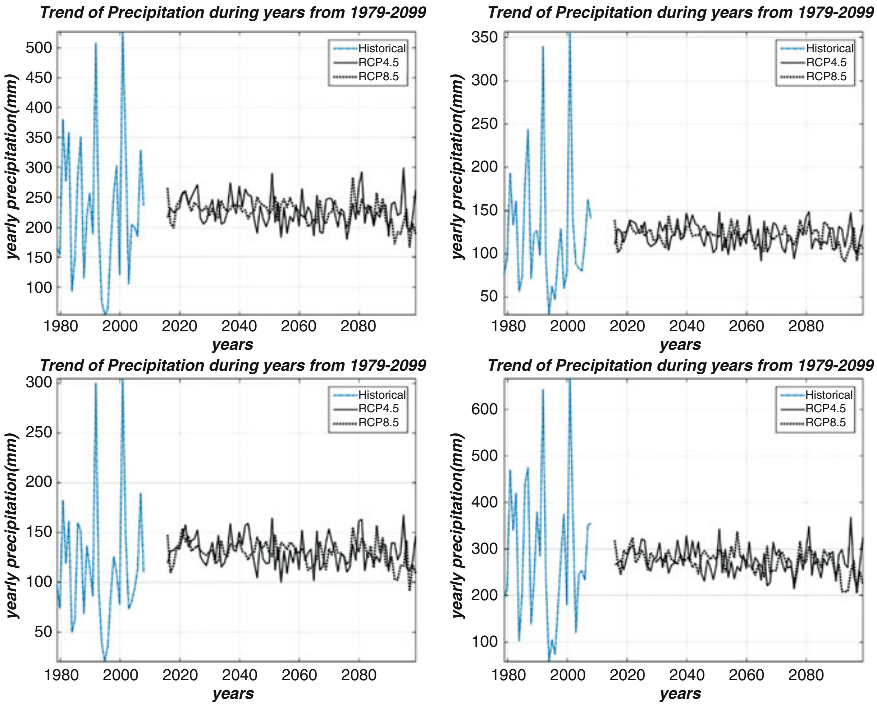

Fig. 6.8 Trend of precipitation in the future in comparison to the past in four stations located in the central and eastern portion of the basin

time period was selected as a significant event. The characteristics of this significant historical drought were the *severity* of the SPI value of −4.39, the *duration* of 6 months, and the *peak intensity* of the SPI value of −1.36. Based on these characteristics, the return period values for the historical period (1979–2008) were calculated using tri-variate copula functions for all grids in Isfahan province. Afterward, spatial maps were generated using the inverse distance weighting (IDW) method. Then, 15 GCMs' data were downloaded, and the SPI values and drought characteristics were computed for each grid within the basin for the near future (2016–2057) and distant future (2058–2099) under RCP4.5 and RCP8.5. The frequency of selected significant drought was calculated for the distant and near future using tri-variate copula functions and generated spatial maps for each GCM model under each scenario. The results are discussed below.

6.3.1 Historical Drought

Figure 6.9 shows the frequency of significant drought in the historical period (1979–2008) in Isfahan province. The low values illustrated the higher occurrences

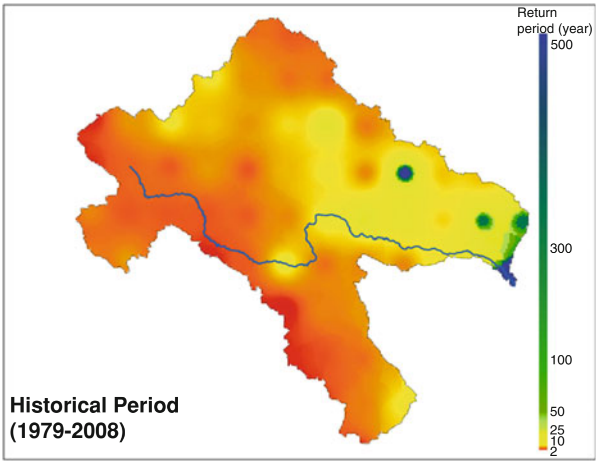

Fig. 6.9 Return period of severe drought (severity equal to SPI value of less than −4.39, duration equal to more than 6 months, and peak intensity of SPI value equal to less than −1.36) based on results of tri-variate copula of severity-duration-peak intensity in the historical period (1979–2008)

of drought. According to the tri-variate copula frequency analysis for the historical period, the return period for different parts of the basin ranged from 2 years to about 50 years. This diversity in the range of the calculated return period was reasonable, given the complex topography of the basin. It was clear that the major parts of the basin suffered from significant drought (severity of less than −4.39, duration of more than 6 months, and a peak intensity of less than −1.36) with less than 10 years as return period between 1979 and 2008. It is clear the return period of severe drought in the downstream part and the Roodasht area is less than 10 years and about 5 years in the past. This also corresponded to the decreasing trend in the precipitation in most parts of the basin, with the worst-case example of the river becoming completely dry several times in the city of Isfahan. More frequent drought events in the Roodasht area caused more problems in the agricultural activities in the past.

The upstream reaches of the basin are located in the mountains and the downstream reaches—namely, Roodasht area—are mostly confined to the wilderness. Higher precipitation values were expected in the upper region; however, drought was severe in those regions when compared with the downstream region for the historic period. This was likely because the upstream region is located in a mountainous area and the downstream in a desert area, so the annual precipitation in the upstream area was normally much more than the precipitation totals in the downstream area. Also from the precipitation analysis, the decreasing trend in the upstream region was much more severe. Thus, the absolute SPI value for the upstream region was more, resulting in severe drought. Although the annual precipitation value in the downstream reach was low, the decreasing trend in this part was not significant, and hence the SPI value was not high in contrast to the upstream portions of the basin.

6.3.2 *Impacts of Climate Change on the Drought Under RCP4.5 Scenario*

Based on the fifth assessment report established by the IPCC, RCP4.5 shows the stabilized gas emissions. For the RCP4.5 scenario, the SPI values were calculated for each grid within the basin. Then the duration, severity, and peak intensity of the drought were calculated based on computed SPI. The tri-variate copula was then fitted to these margins to estimate the return period of the severe drought. Figure 6.10

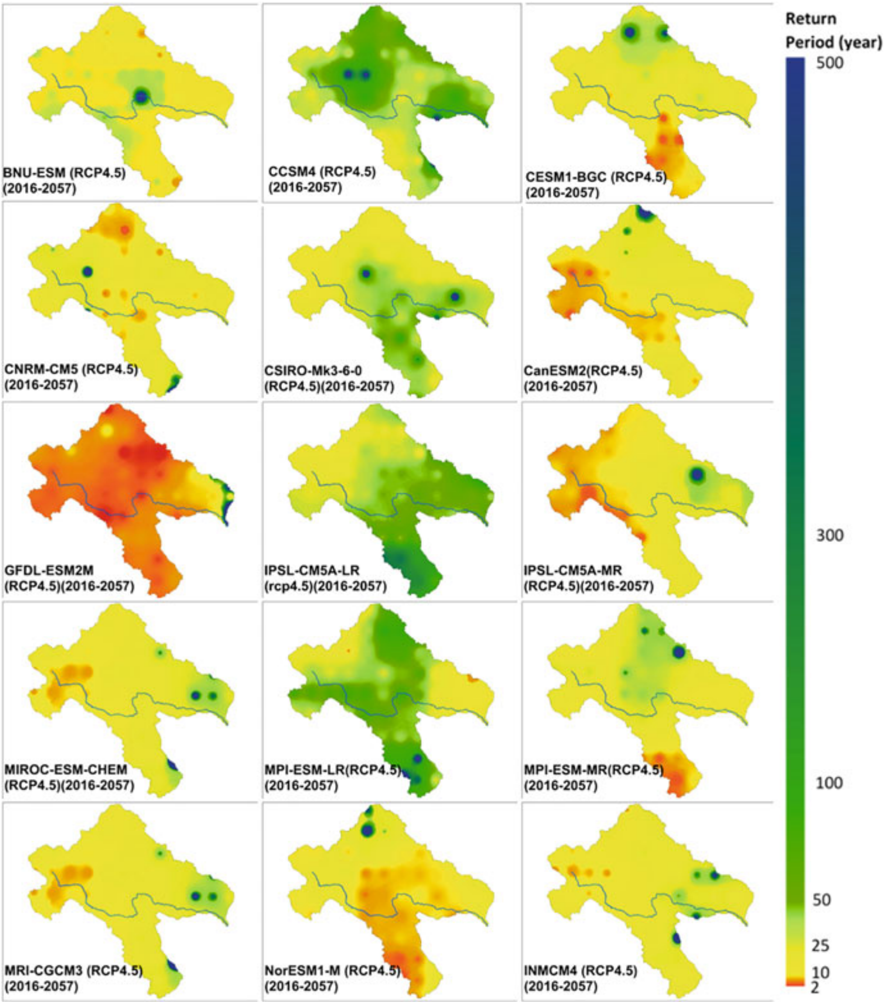

Fig. 6.10 Spatial analysis of return period based on tri-variate copula of severity-duration-peak intensity in the near future (2016–2057) using 15 GCMs with RCP4.5 for severe drought (severity equal to SPI value of less than −4.39, duration equal to more than 6 months, and peak intensity of SPI value of less than −1.36)

shows a spatial analysis of tri-variate copula in the near future period (2016–2057) on the basis of 15 GCM models within the framework of the RCP4.5 scenario. During this period, the GFDL-ESM 2 M model shows an almost similar drought condition as in the historical period in the upstream of the basin. However, in the downstream part and Roodasht area, more frequent severe droughts are expected in the near future, and the return period of intense drought is about 2 years in this part. Other models predicted an almost similar condition with the past for the downstream parts. The models CCSM4, CSIRO-MK3-6-0, IPL-CM5A-LR, and MPI-ESM-LR show better conditions with less frequent intense drought in the same period and a frequency of about up to 50 years for the severe and significant drought in the downstream part and Roodasht area. On the other hand, the frequency of severe drought would be expected to be similar to the past condition in the Roodasht area and the eastern part of the basin, so that the range and spatial variability of the drought frequencies need to be cautiously interpreted with the context of water resources management.

The range in the frequency in the distant future (2058–2099) is more floating as is shown in Fig. 6.11 based on the GCM models under the RCP4.5 scenario. The GFDL-ESM 2M model predicted that the whole basin was prone to severe drought with frequency being less than 5 years and about 2 years. Also, BNU-ESM shows more frequent droughts for the Roodasht area with a return period of about 2 years. The INMCM4 model shows a 50-year return period for severe drought in the entire basin. Also, in the CNRM-CM5 GCM model, increasing return periods can be seen in the entire basin which could be interpreted as the equivalent of decreasing frequencies of severe drought in the future. CESM1-BGC, CanESM2, and IPSL-CM5A-LR GCM models predicted less frequent intense drought in the eastern part of the basin, namely, the Roodasht area and the return period of severe drought is about 50 years in this part. Other GCM models show a similar condition of intense drought frequency with past conditions in the eastern part.

Regardless of the upstream or downstream regions within the basin, there seemed less difference in the drought conditions between near and distant future, but the frequency of intensive drought (i.e., less than 10-year return period drought) in the basin would be less, in comparison to the past based on the GCM models under RCP4.5. In the other words, it can be said that precipitation would increase slightly in the future compared with the past period (1979–2008); hence, the return period of severe drought in the basin could be less than 25 years based on the selected RCP4.5 scenario for the future. The precipitation increasing trend can lead to better conditions for agricultural activities, and consequently, more agricultural products can be expected from the Roodasht area based on RCP4.5 in the near and distant future.

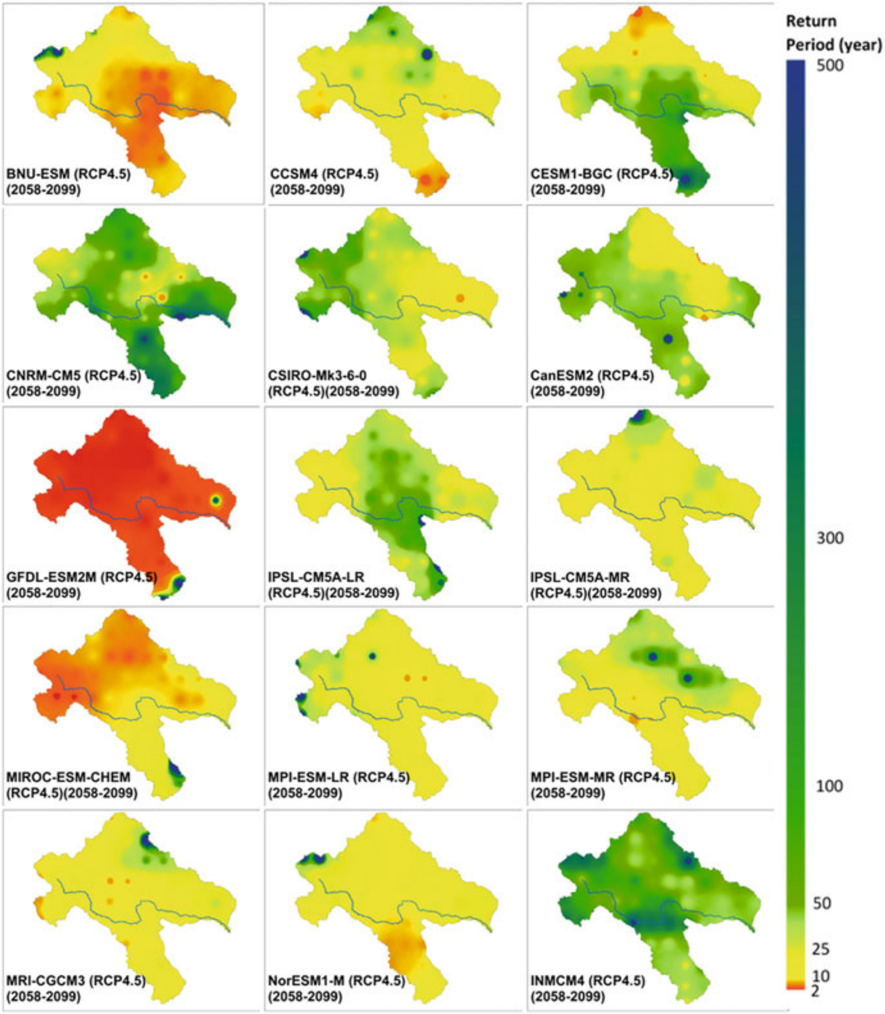

Fig. 6.11 Spatial analysis of return period based on tri-variate copula of severity-duration-peak intensity in the distant future (2058–2099) using 15 GCMs with RCP4.5 for severe drought (severity equal to SPI value of less than −4.39, duration equal to more than 6 months, and peak intensity of SPI value equal to less than −1.36)

6.3.3 Impacts of Climate Change on the Drought Under RCP8.5 Scenario

SPI values were calculated using the downloaded precipitation data from 15 GCMs under RCP8.5. The severity, duration, and peak intensity of the drought were then calculated based on the SPI. Thereafter, the tri-variate copula was computed to estimate the return period of intense drought in the future. The impacts of climate

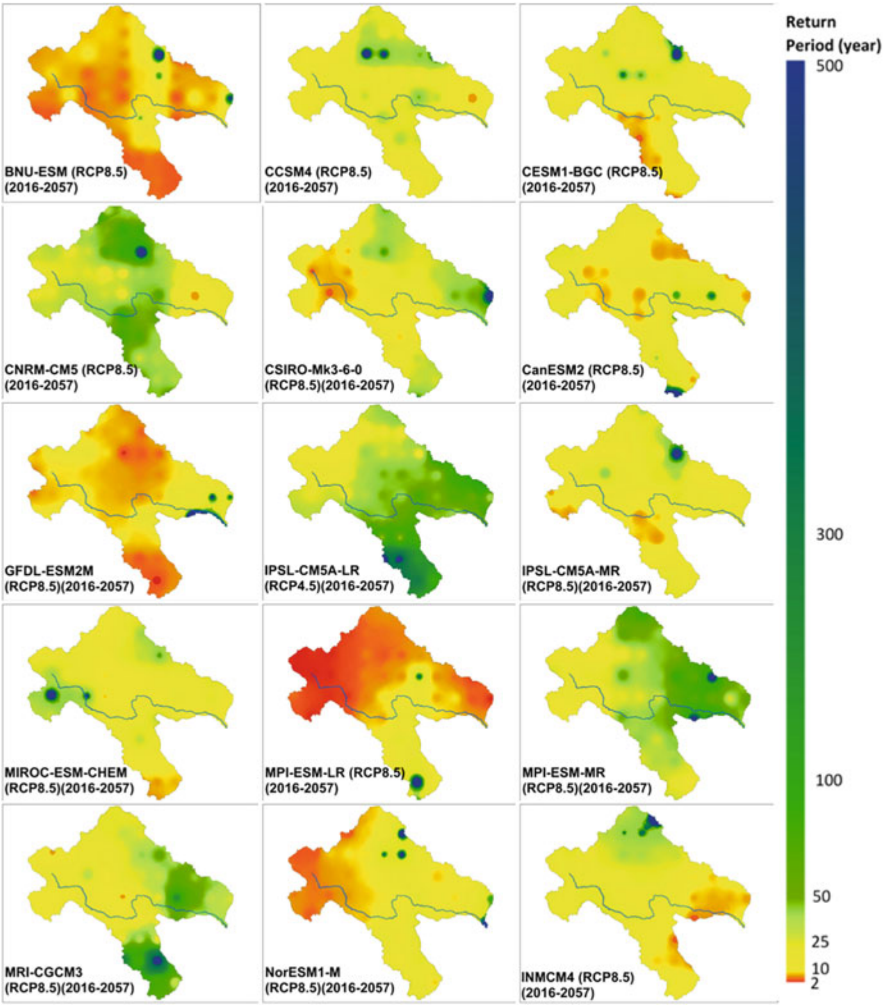

Fig. 6.12 Spatial analysis of return period based on tri-variate copula of severity-duration-peak intensity in the near future (2016–2057) using 15 GCMs with RCP8.5 for severe drought (severity equal to SPI value of less than −4.39, duration equal to more than 6 months, and peak intensity of SPI value equal to less than −1.36)

change on the drought based on 15 GCM models under RCP8.5 in the near and distant future are shown in Figs. 6.12 and 6.13, respectively. For the near future period (2016–2057) in the MPI-ESM-LR GCM model, the upper and lower sections appeared to be more drought-prone with more frequent drought events, while the return period of vigorous drought increased relative to the past in the middle section of the basin, indicating less drought over this area. Most GCM models indicated that the vigorous drought return period increased in the near future and has fewer frequent drought periods in the basin than in the past period. In some cases, the

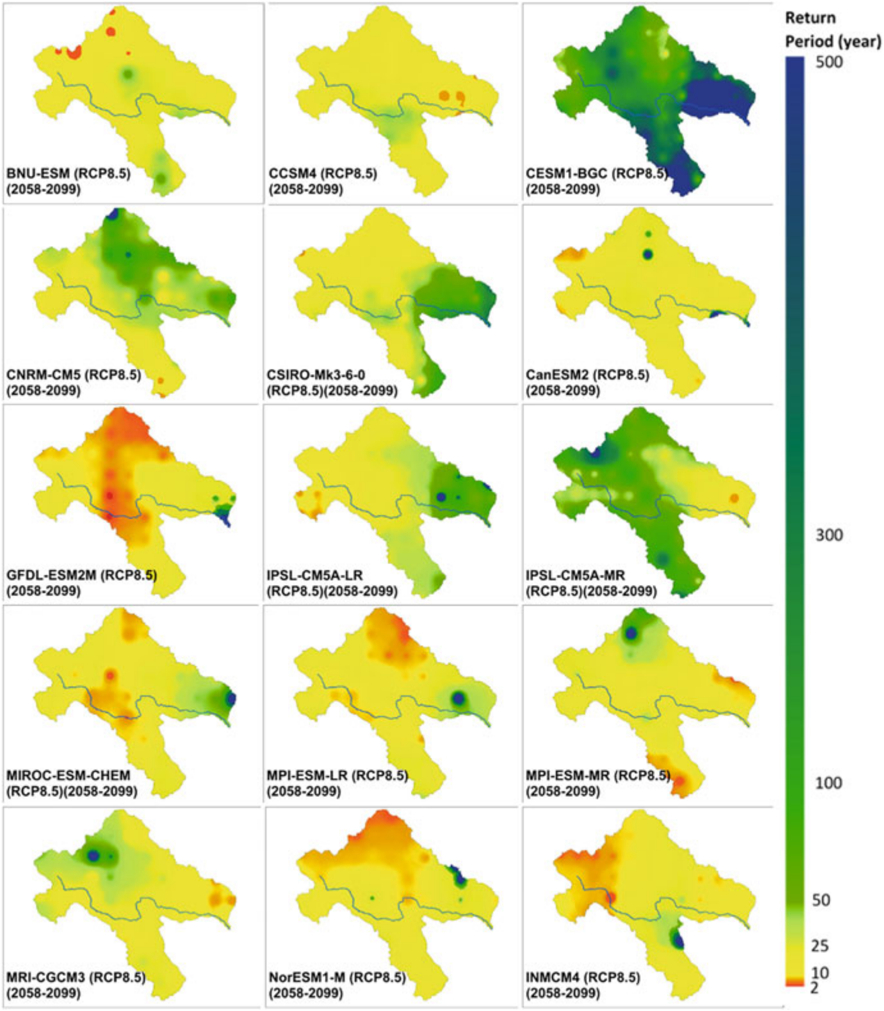

Fig. 6.13 Spatial analysis of return period based on tri-variate copula of severity-duration-peak intensity in the distant future (2058–2099) using 15 GCMs with RCP8.5 for severe drought (severity equal to SPI value of less than −4.39, duration equal to more than 6 months, and peak intensity of SPI value equal to less than −1.36)

return period for the severe drought is up to 50 years. In the eastern parts, including Roodasht, the BNU-ESM and INMCM4 models indicate a 2-year return period of intensive drought, which is more frequent than the drought frequency in the historical period in this area. For this part of the basin, the MRI-CGCM3, MPI-ESM-MR, IPSL-CM5A-LR, and CNRM-CM5 GCM models show less frequent severe droughts and the return period of intense drought of up to 50 years.

The changes in the return period in the distant future were larger and ranged between 10 and 400 years. According to the CESM1-BGC GCM model, almost the entire basin had return periods of more than 100 years and in some sections, including Roodasht, even more than 300 years. In the IPSL-CM5A-MR GCM model, the upper basin had a return period of more than 50 years, but there is no specific difference between past and distant future drought frequency in the eastern part of the basin. Based on CSIRO-MK3-6-0 and IPSL-CM5A-LR, the return period of violent drought in the western part of the basin would increase by up to 100 years compared to the past, and in the eastern part, it would be approximately 25 years. Furthermore, the CNRM-CM5 GCM model predicted less frequent violent drought events in the eastern and central parts of the basin with return periods of about 100 years. Based on this GCM, the return period of intensive drought events in the western part would extend to about 10 years in the distant future. Nevertheless, it is essential to consider appropriate water management solutions to prepare for future drought and likely water shortages in the basin, especially in the Roodasht area.

Altogether, for the near future, Figs. 6.10 and 6.12 indicated that in GFDL-ESM 2 M under the RCP4.5 scenario in the western part of the basin, there would be slightly better conditions and less frequent droughts, but in the eastern part, the violent drought frequency would increase. Furthermore, MPI-ESM-LR under the RCP8.5 scenario shows severe drought-prone areas were similar and even more frequent to that of the past period in the eastern and the western parts. The INMCM4 GCM model indicated the return period of about 25 years in the eastern part which is less frequent in comparison to the past, but in the Roodasht area, the return period decreases to 5 years, which is more frequent than in the past. Besides these GCM models, other models have shown that the frequency of intense drought could be less or similar to the historical period in eastern parts. In models CCSM4, CSIRO-MK3-6-0, IPSL-CM5A-LR, and MPI-ESM-LR under RCP4.5 and CNRM-CM5, IPSL-CM5A-LR, MPI-ESM-MR, and MRI-CGCM3 under RCP8.5, the return period of vigorous drought was more than 50 years in the Roodasht area. Generally, less or similar frequency of intense drought was expected in the near future for the Roodasht area. As shown in Figs. 6.11 and 6.13, BNU-ESM and GFDL-ESM 2 M model under RCP4.5 projected more severe droughts with the return period of about 5 years for the Roodasht area during the distant future period. CESM1-BGC, CNRM-CM5, CanESM2, IPSL-CM5A-LR, and INMCM4 under RCP4.5 and CESM1-BGC, CNRM-CM5, CSIRO-MK3-6-0, and IPSL-CM5A-MR under RCP8.5 illustrated return periods of more than 50 years and even more than 100 years for vigorous drought in Roodasht in the distant future. Other GCM models demonstrated less or similar frequency droughts in the eastern part of the basin in the distant future compared to the past. In general, in the distant future, frequencies of drought could be less in Roodasht, but a high-resolution analysis was required to validate these results.

Based on Eq. (6.6) to calculate the return period, there is no unique number of drought characteristics (e.g., duration, severity, and peak intensity) for each return period. Therefore, it is helpful to use contour plotting to show the specific return period with different durations, severity, and peak intensity. Since there are three

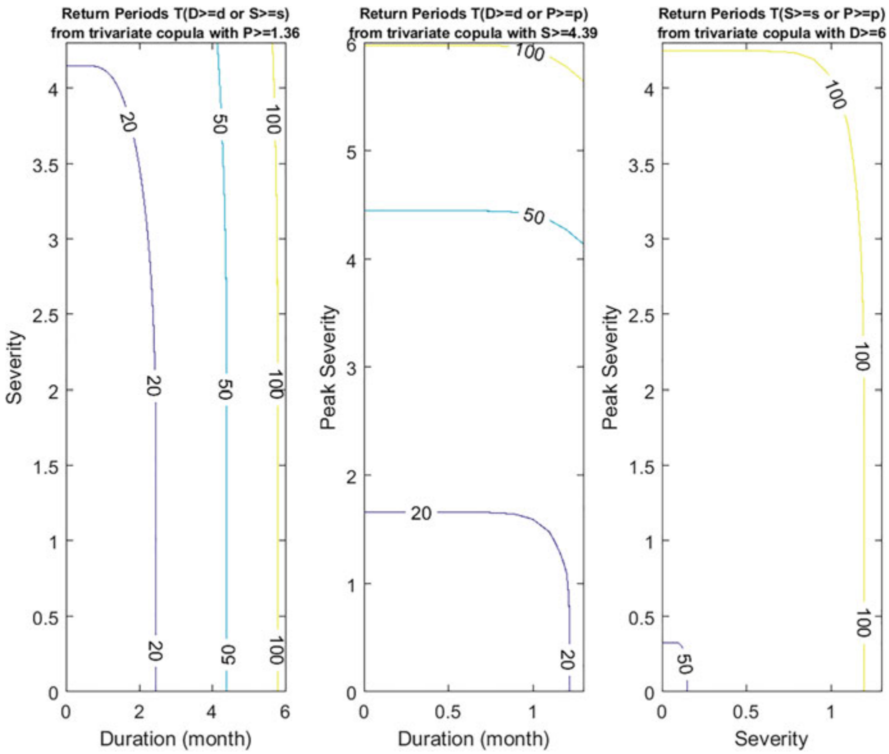

Fig. 6.14 Contour plots of the return period based on tri-variate copula of severity-duration-peak intensity in a station located in the Roodasht area based on MRI-CGCM3 GCM model under the RCP 4.5 during (2016–2057)

drought characteristics that must be shown on the plot, the plot should be the three-dimensional plot with some sheets that are representative of the return period values. This type of plot is hard to understand. It was therefore decided to fix a value for one of the drought characteristics (e.g., duration, severity, and peak intensity) and to draw two-dimensional contour line plots, as shown in Figs. 6.14 and 6.15. Figure 6.14 shows the contour lines of the return period based on tri-variate copula in a station located in the Roodasht area in the near future (2016–2057) using MRI-CGCM3 model under RCP4.5 data.

Figure 6.15 illustrates the contour lines of the return period based on tri-variate copula in a station in Roodasht in the distant future (2058–2099) using MIROC-ESM-CHEM model under RCP8.5. In the first part of these figures, the peak intensity value was set to the SPI value of -1.36, which corresponds to the peak intensity of the severe drought. In the second part of these figures, the severity value corresponds to the SPI value of -4.39, the severity of the severe drought. In the third part, the value of the duration was fixed to the duration of the severe drought, in this case, 6 months. Using this type of plots, with the determined fixed values, the value

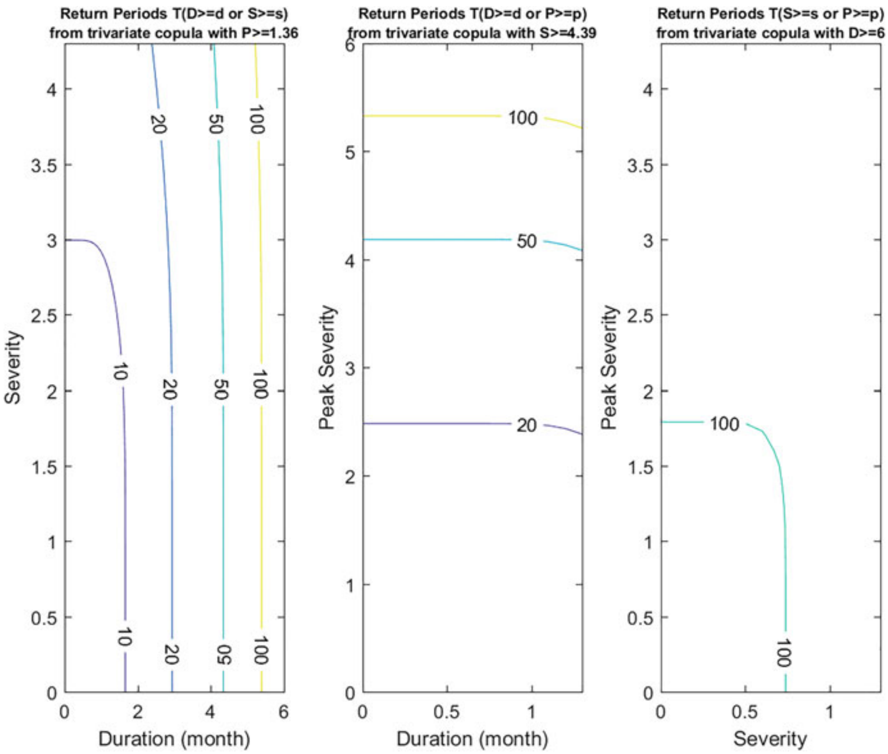

Fig. 6.15 Contour plots of the return period based on tri-variate copula of severity-duration-peak intensity in a station located in the Roodasht area based on MIROC-ESM-CHEM GCM model under the RCP 8.5 during (2058–2099)

of the other drought characteristics can be found for each return period. In the second part of Fig. 6.14, the severity value was fixed to −4.39. In this figure, the drought return period with a duration of 1 month and the peak intensity of 4.5 is about 50 years. This type of contour plots can help water managers and decision-makers to formulate a clearer and more precise understanding of the drought events in the future in the catchment area.

6.4 Conclusion

The future droughts in the Roodasht region in the Zayandeh Rud basin were assessed using the SPI drought index and tri-variate copula techniques under climate change conditions. SPI was used to calculate the duration, severity, and peak intensity of the drought in the basin for the historical period (1979–2008). The 90th percentile of drought duration, severity, and the peak intensity in the past occurrence was selected as a significant drought event, and the pertinent parameters were severity ≤ -4.39, duration ≥ 6, and peak intensity ≤ -1.36. Exponential, gamma, log-normal, and Weibull distribution functions were chosen to fit the drought characteristics for the historical data. In addition, the MLE method was used to estimate the parameters of each distribution. The best-fitting distribution for severity, duration, and peak intensity was selected based on the BIC method.

The results show that the best distribution is log-normal for the duration and severity of the drought, and the exponential distribution is the best for the peak intensity of the drought. Due to the high correlation between the drought characteristics, three common copulas in the Archimedean family (Clayton, Frank, and Gumbel-Hougaard) and two common copulas in the meta-elliptical families (*t* and normal) were used to create the tri-variate copula to evaluate the return period of past and future droughts in this study. The best copula function for tri-variate copula was normal copula based on the BIC method. The impacts of climate change on the drought were investigated using 15 GCM models under RCP4.5 and RCP8.5 scenarios of AR5. The future period was divided into two periods of the near future (2016–2057) and the distant future (2058–2099) to investigate the effects of climate change on drought conditions in the future. Finally, the return period for each model under each scenario was illustrated on the map using the IDW method.

The results of GCM models for both RCP8.5 and RCP4.5 indicated that the specific increasing or decreasing trend of future precipitation in the basin can't be predicted. However, most GCM models predicted a slightly probable increase in precipitation trend in the eastern parts of the basin including the Roodasht area and also a decrease in precipitation in the western portion of the basin.

The return period of intensive drought for the historical period (1979–2008) for the Roodasht area is less than 10 years, and this area of the basin suffered from violent drought during this period. The results of GCMs under RCP4.5 for the near and distant future are similar and show a slightly lower frequency or the same frequency of severe drought compared to the past for the Roodasht area. GCMs under RCP8.5 for the near and distant future predicted a similar condition of drought frequency in the Roodasht area to the historical period. Overall, the frequency of intense drought in the Roodasht area for the near and the distant future would be somewhat less than in the past, and the return period is expected to increase from less than 10 years in the past to less than 25 years in the future. Despite an insignificant increase in future precipitation based on GSM models for the eastern part of the basin, including Roodasht area, planning for long-term drought in the basin is the key to managing the water resources in the agricultural areas in this basin including Roodasht, due to uncertainties in those predictions in the warming world. Drought affects water resources and can reduce water consumption in several sections, e.g., in the form of potable water and water for agricultural activities. As the quality and yield of agricultural products depend on the available water, the water deficit leads to a restriction of agricultural activities. This could adversely impact on farmers' lives and, consequently, on society. It is therefore very important for decision-makers to properly plan and manage water resources during the drought period.

It was also indicated that the use of contour plots showing the specific return periods with different duration, severity, and peak intensity is helpful for water managers in order to understand the drought conditions of the basin in the future precisely.

It is recommended to compare the results of research using AR4 with the current study to find the preference of AR5 in comparison with AR4 in the case of the copula. Also, it is worthwhile to analyze the uncertainty of the prediction by the GCMs and to estimate the probability levels for each model. In addition, it will be advantageous in future studies to analyze the uncertainty of calculated past return periods.

Acknowledgments With appreciation to the Iran Meteorological Organization for preparing the much-needed precipitation data. Also, the first author wishes to thank the Biological System and Engineering Department at Virginia Tech University for providing the opportunity of using its facilities and for the various consultations with the experts at Virginia Tech.

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Chapter 7
Hydrological Modeling of Spatial and Temporal Changes of Blue and Green Water Resources in the Zayandeh Rud River Basin

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7.1 Introduction

Population growth and economic development along with intermittent droughts have led to a water crisis in many arid and semi-arid regions of the world (UN Water 2009; Vörösmarty et al. 2010). According to the World Water Organization (WWO), roughly half of the world's population will live in areas with water stress in 2030. Meanwhile, based on the Intergovernmental Panel on Climate Change report (IPCC 2007), variations of precipitation and temperature due to anthropogenic forcing signals (containing the rise of greenhouse gases) have had considerable effects on the hydrological cycle and water resources management (Trenberth 2011; Terink et al. 2013; Wan et al. 2015; Hegerl et al. 2018; Snyder et al. 2019). There are millions of people living in areas experiencing serious shortages of water availability (Pereira et al. 2009; Seneviratne et al. 2012). Thus, a comprehensive assessment and an effective water resources management are vital for understanding the available water endowments as well as enhancing water management plans toward a sustainable, efficient, and instrumental usage of scarce freshwater resources (Vörösmarty et al. 2010; Afshar and Hassanzadeh 2017; Maila et al. 2018; Chowdhury 2019).

Freshwater availability is important for the security of food, ecosystem sustainability, public organization, etc. Globally, with increasing population growth, the shortage of freshwater, particularly in arid and semi-arid regions, may result in a water stress issue (Zuo et al. 2015). The agricultural sector, as the largest water user due to an increasing population, is more closely related to freshwater availability. The cycle of freshwater, by considering the agricultural sector, could be divided into two main parts of "blue" and "green" water resources by the hydrological processes and storage types involved. The idea of blue water (BW) and green water (GW) was first introduced by Falkenmark (1995) and was then developed by other researchers (Falkenmark and Rockström 2006; Schuol et al. 2008; Faramarzi et al. 2009). BW is defined as the sum of surface runoff or water yield (WYLD) and deep aquifer recharge (DA_RCHG), which are stored in rivers, lakes, reservoirs, shallow aquifers, and wetlands and are capable of being directly used for human consumption (Falkenmark 1995). Green water flow (GWF) is the actual evapotranspiration (ET) distributed to the atmosphere via a mix of evaporation from soil and water and the transpiration from vegetations. Green water storage (GWS) is also the stored water content in soil profile (SW) at the end of a timespan (Falkenmark and Rockström 2006; Hoekstra et al. 2011; Rodrigues et al. 2014).

Globally, the average annual GW consumption on rainfed and irrigated cropland is in the order of 5000 km^3/year, which is almost three times more than BW consumption (Rockström 1999; Falkenmark et al. 2004). GWS is a renewable resource because it can potentially generate economic returns, as it is the source of the rainfed agriculture. The GWF is composed of the actual evaporation (the nonproductive part) and the actual transpiration (the productive part), commonly referred to together as the actual evapotranspiration. On the other hand, GW originates from the naturally infiltrated water, which is more and more being thought of as a manageable water resource (Falkenmark et al. 2004).

In arid and semi-arid regions (like the Zayandeh Rud river basin, ZRRB), GW resources play an essential role in crop production as well as the provision of ecosystem services (Falkenmark 1995; Cheng and Zhao 2006). Many studies in the world focus on BW and GW with spatial and temporal variations and the importance of these components in different watershed basins for strategic decision-making on food security (Sulser et al. 2009; Zang et al. 2012; Veettil and Mishra 2016; Liu et al. 2017; Badou et al. 2018; Yuan et al. 2019).

The Zayandeh Rud river basin (ZRRB), with a wide range of climate conditions, is expected to face changes in both water quantity and quality. Given the strategic importance of the Zayandeh Rud river basin as the only water supply of central Iran, not enough work has been initiated to study the spatial and temporal changes of these components in the basin. Therefore, the main objective of this chapter is to survey and discuss the spatial variations of water resources components (e.g., BW, GWF, and GWS) in the ZRRB, especially in the eastern part of the basin during a period of 20 years. In addition, we will describe how the water resources components in basin levels over the four period times of the timespan 1995–2014 have changed (period 1, 1995–1999; period 2, 2000–2004; period 3, 2005–2009; and period 4, 2010–2014). The impact of climate parameters such as the influence of precipitation on the availability of water resources in the basin has also been investigated.

7.2 Study Area

Our study area covered the entire ZRRB (located between 31° 15′ to 33 °45′ north latitude and 50 °2′ to 53 °20′ degrees east longitude) with an area of about 26,280 km^2 (Fig. 7.1). The climate is semi-arid in the uplands (west) and arid in the lowlands (east). Unreliable rainfall patterns, uneven distribution of water resources, frequent and prolonged droughts, and human factors such as population growth and economic development present a significant concern for the availability, access, reliability, and utilization of water resources in the basin. Precipitation occurs mainly in winter months from December to April, and temperatures reach 35 °C in July while it drops to −5 °C in January. The average annual reference evapotranspiration is reported to be 1500–1600 mm/year^{-1} for the basin (Madani and Mariño 2009; Gieske et al. 2002). Low and unreliable rainfall in the central and eastern portions of the basin have caused irrigation to be considered as essential to the cultivation of crops (wheat, barley, silage plants, potatoes, cotton, paddy orchards, etc.). There are 2600 km^2 of irrigated lands in the basin, with water derived from the 9 main irrigated networks of the Zayandeh Rud river, wells, qanats, and springs in lateral valleys. On the other hand, rainfed forms can be seen in large parts of the western portions upstream of the Zayandeh Rud dam. Therefore, green water resources and their changes in this part of the basin are very important. A greater description of the study area is given by Faramarzi et al. (2017).

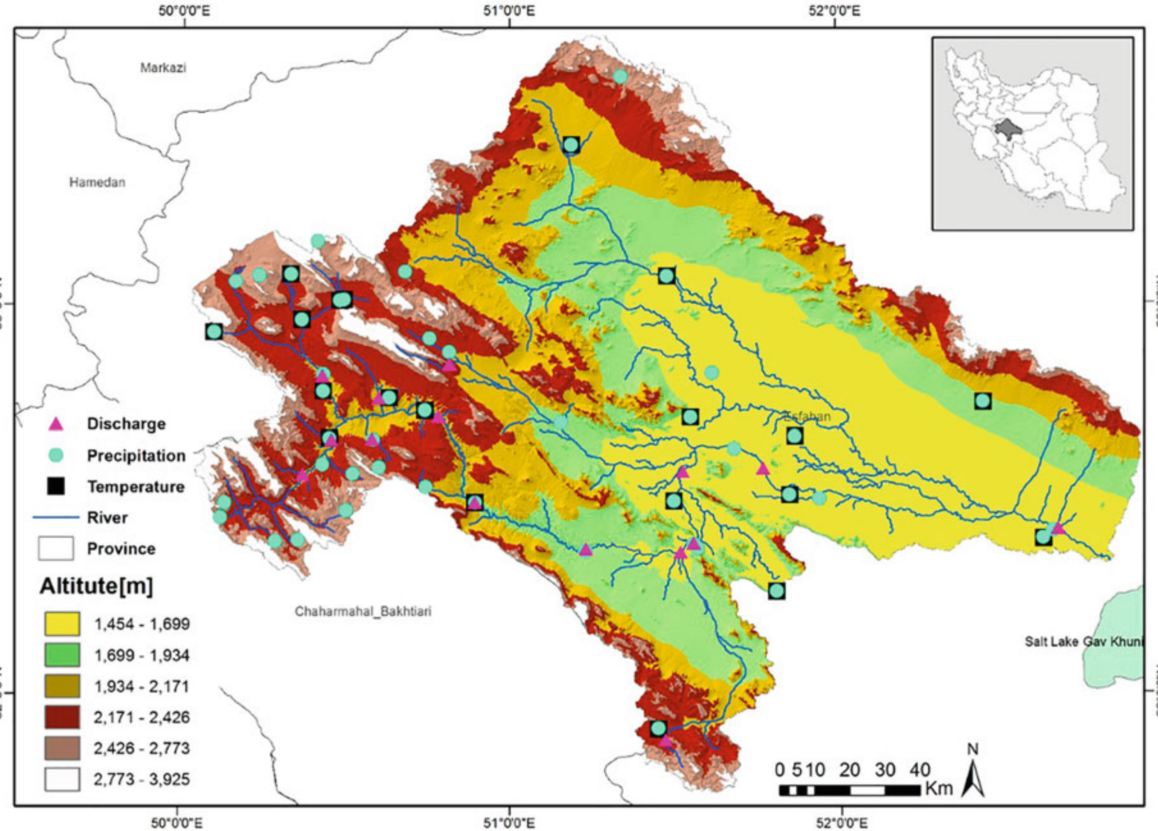

Fig. 7.1 Geographic location of the ZRRB, the SRTM 90 m DEM map of the study area, and the spatial distribution of the model used precipitation, temperature, and hydrometric gauges

7.3 Methodology

7.3.1 SWAT-Zayandeh Rud

To model the spatial variations of water resources components (i.e., BW, GWF, and GWS) in the ZRRB, we used the SWAT-Zayandeh Rud model developed by Faramarzi et al. (2017) in the frame of the IWRM-Zayandeh Rud project. The main goal of the IWRM-Zayandeh Rud project was to simulate both the ZRRB and the upstream catchments of the Karoon-Dez watersheds, which are considered the main sources of water for the Zayandeh Rud basin, through current and future water development and transfer projects. Therefore, the SWAT-modeled area was larger than the Zayandeh Rud basin (with a total number of 370 sub-basins). In the current study, we have only modeled the Zayandeh Rud river basin and a total of 286 sub-basins were delineated and modeled for the entire basin (see Fig. 7.2). Furthermore, in the study by Faramarzi et al. (2017), SWAT 2009 was used, and the simulation period was from 1990 to 2009 by considering the first 3 years as the model warmup. For more information on the study area, the data used, and the hydrological modeling of the Zayandeh Rud river basin in the frame of the IWRM-Zayandeh Rud project, see Faramarzi et al. (2017).

7.3.2 Improvement of the SWAT-Zayandeh Rud

In addition to a different study area compared to the study of Faramarzi et al. (2017), the calibration performance (especially in downstream stations) was not desirable in the developed model by them (see Fig. 7.3). For instance, their simulation results revealed a considerable stream flow contribution from Shoor, Dastkan (Northern Tributaries), and Morghab rivers into the Zayandeh Rud main river which does not correspond to the actual condition in the basin. This over estimation was mainly due to the lack of the water use data based on Faramarzi et al. (2017). To solve this problem, we tried to gather and complete the management data, consider water allocation to various uses within these subcatchments in the model, and also adjusted physical parameters to represent actual processes related to the rain water harvesting projects in the northern tributaries to allow the surface water to infiltrate and recharge the groundwater.

In addition, new sensitivity analysis and recalibration, along with updating climate and management data, were done using SWAT 2012 to improve the quality of the predictions in the current study. For the sensitivity analysis, new parameters related to stream flow and precipitation, other than the 22 parameters tested by Faramarzi et al. (2017), were selected, and their sensitivities were investigated. The parameters were further differentiated by main hydrological regions (see Faramarzi et al. 2017) in order to account for regional and spatial variation in climate and management conditions. Discharge gauges in the basin were separately calibrated

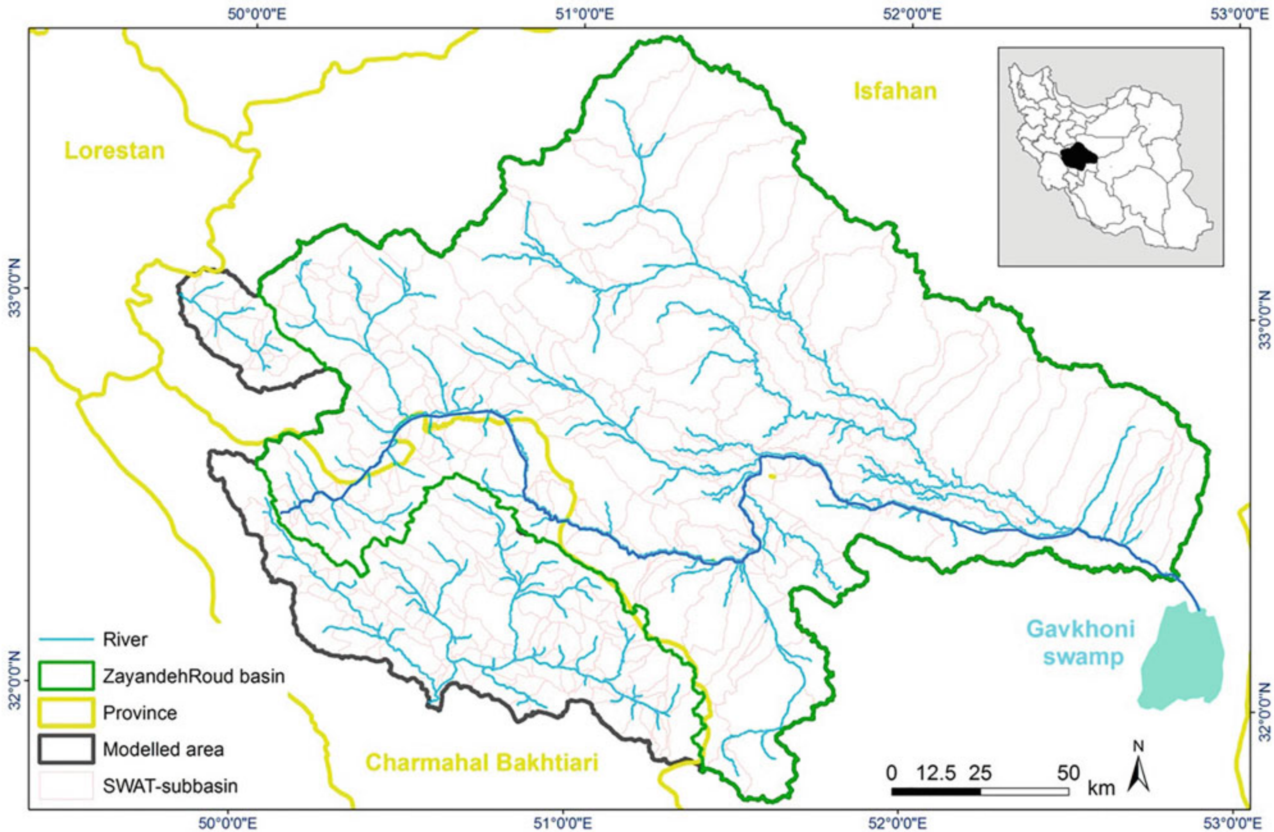

Fig. 7.2 The modeled area in Faramarzi et al. (2017) including Zayandeh Rud river basin (shown with green boundary) and the area from Karoon-Dez river basin (gray boundary)

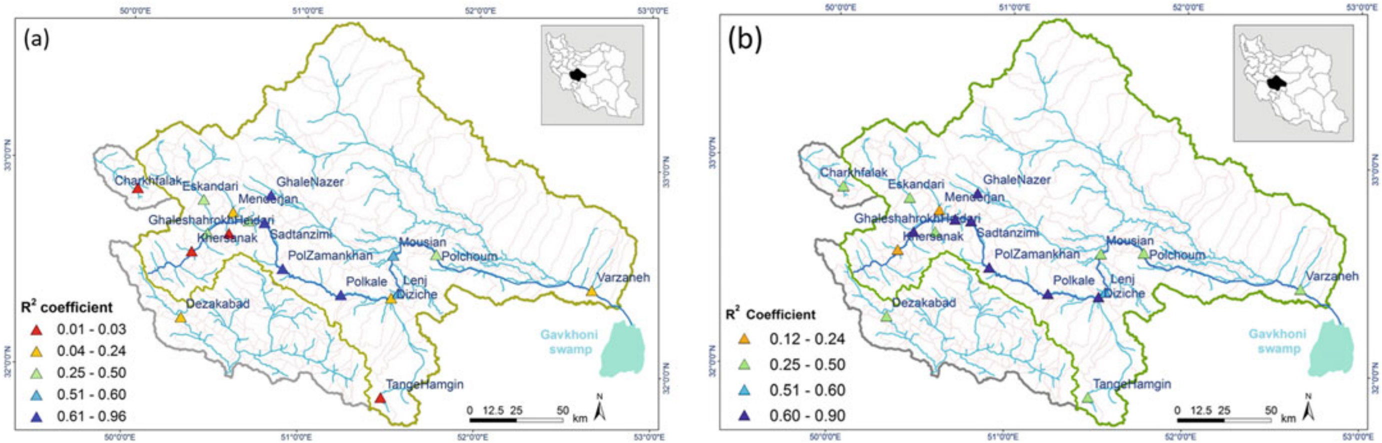

Fig. 7.3 Comparison of observed and simulated discharges using coefficient of determination (R2) for 17 hydrometric stations: pre-calibration (**a**) and post-calibration (**b**) (Faramarzi et al. 2017)

for different water regions using the "regional approach." The program SUFI-2 (Abbaspour 2011) was also used for a combined calibration and uncertainty analysis.

7.3.3 Modeling of Water Resources Components

To meet the ultimate goal of the current study (i.e., modeling of spatial and temporal variations of water resources components in the basin), the simulated monthly data of surface runoff, deep aquifer recharge, soil water contents, and actual evapotranspiration were required from SWAT. To generate these simulations using SWAT, we used our calibrated and validated hydrologic model of the basin including all management measures (i.e., water transfers, water diversion for agricultures, industries, drinking and municipalities, and dam operation) and ran it monthly to predict each investigated water component (BW, GWF, and GWS components) for each SWAT sub-basin. The simulation period was from 1990 to 2014 by considering the first 3 years as the skip years. In order to survey the spatial and temporal variations of BW, GWF, and GWS components in the ZRRB, we also divided the simulation period into four sections: period 1 (1995–1999), period 2 (2000–2004), period 3 (2005–2009), and period 4 (2010–2014). The mid-range (M95ppu) values were also used to represent the estimated water component values. Finally, the spatial and temporal distribution maps of the studied components were prepared in the GIS software environment.

7.4 Results

7.4.1 Improvement of the SWAT-Zayandeh Rud

As mentioned above, some possible improvements (e.g., use of SWAT2012 instead of SWAT2009, new sensitivity analysis, collection of new available management and climate data, revision of temperature parameters especially in the upstream parts of the watershed and use of some nonincluded hydrometric stations in the first phase of the project) were considered to upgrade the performance of SWAT-Zayandeh Rud for the simulation of hydrological behavior in the basin. Comparing the observed and simulated streamflow for investigated hydrometric stations in different regions shows that the overall calibration results for the entire Zayandeh Rud basin are more desirable than for the previous version of the SWAT-Zayandeh Rud (Fig. 7.4).

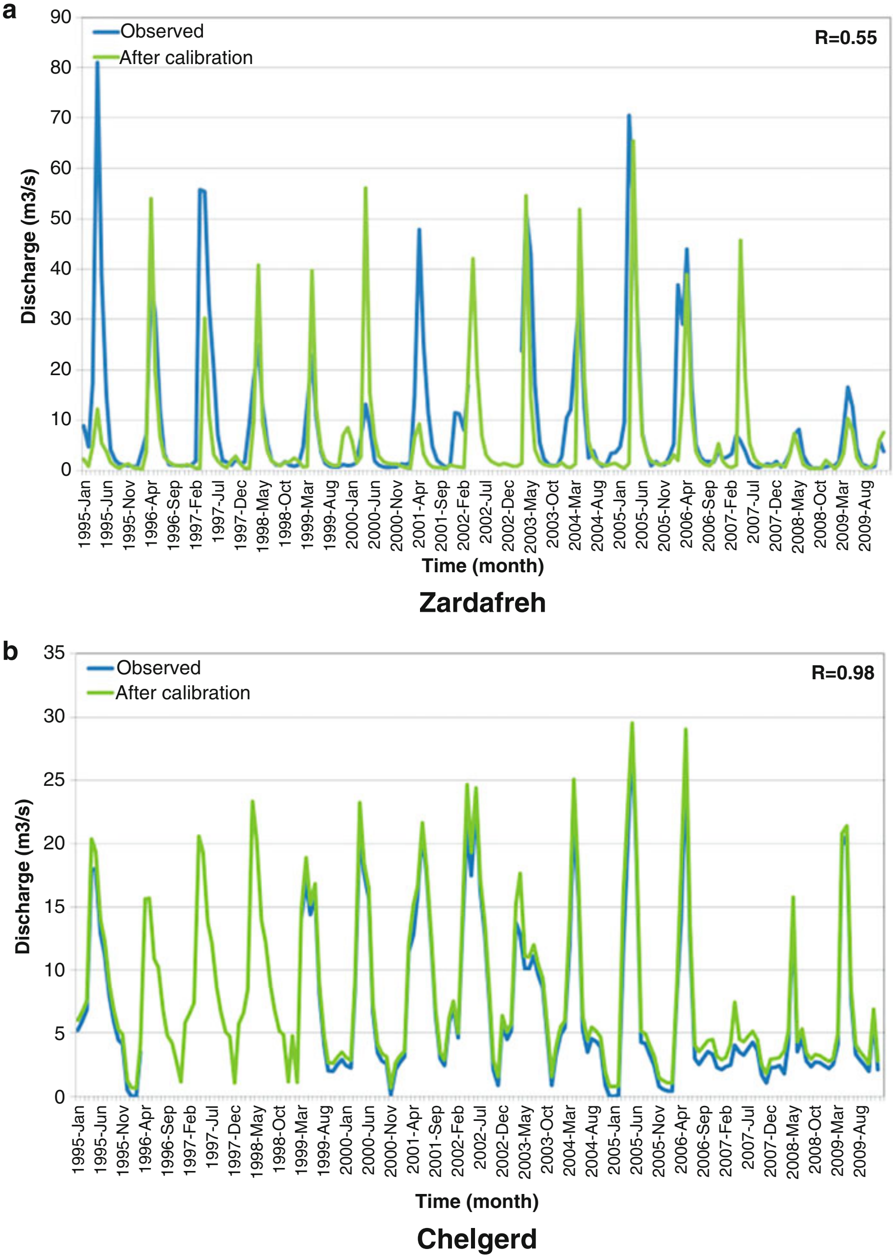

Fig. 7.4 Comparison of observed (blue) and simulated (green) streamflow for hydrometric stations located in ZRRB at final calibration process

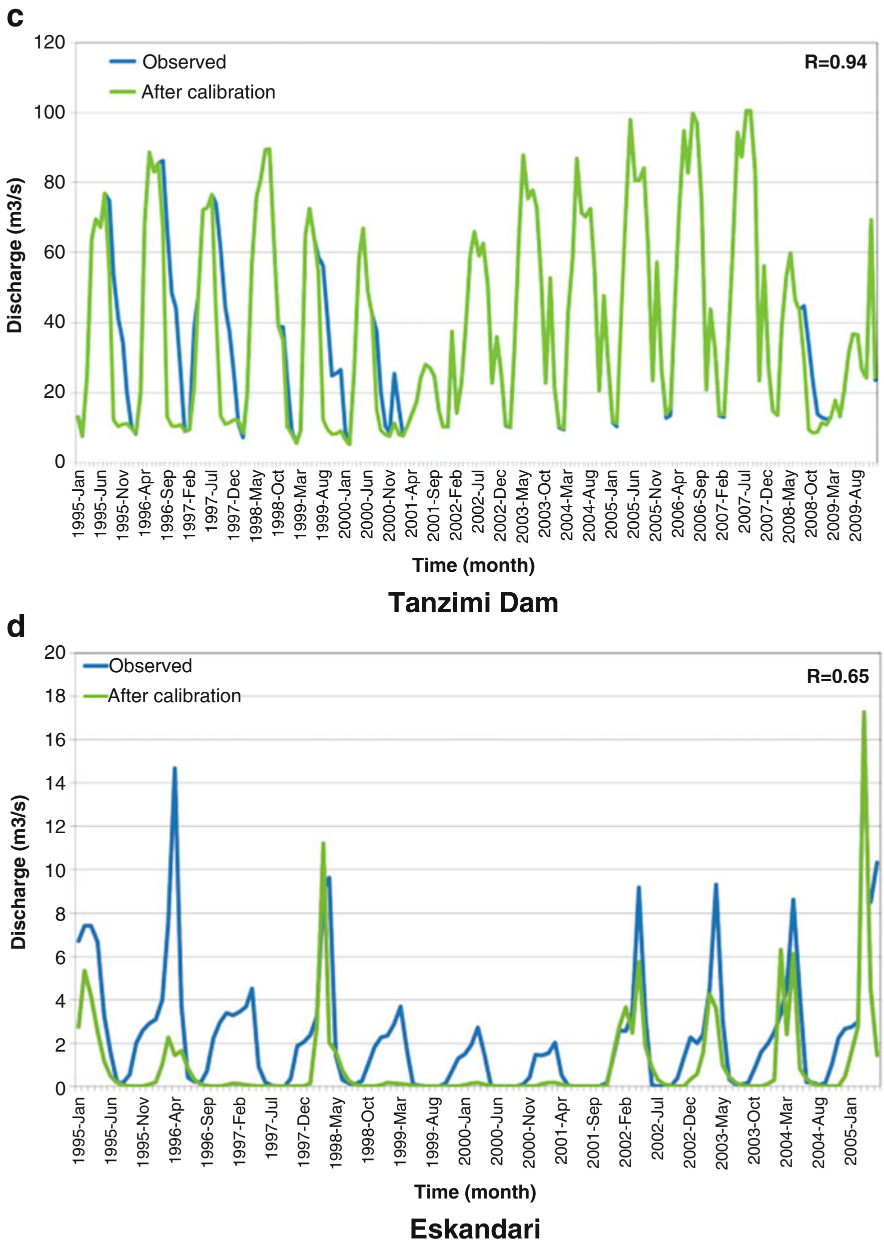

Fig. 7.4 (continued)

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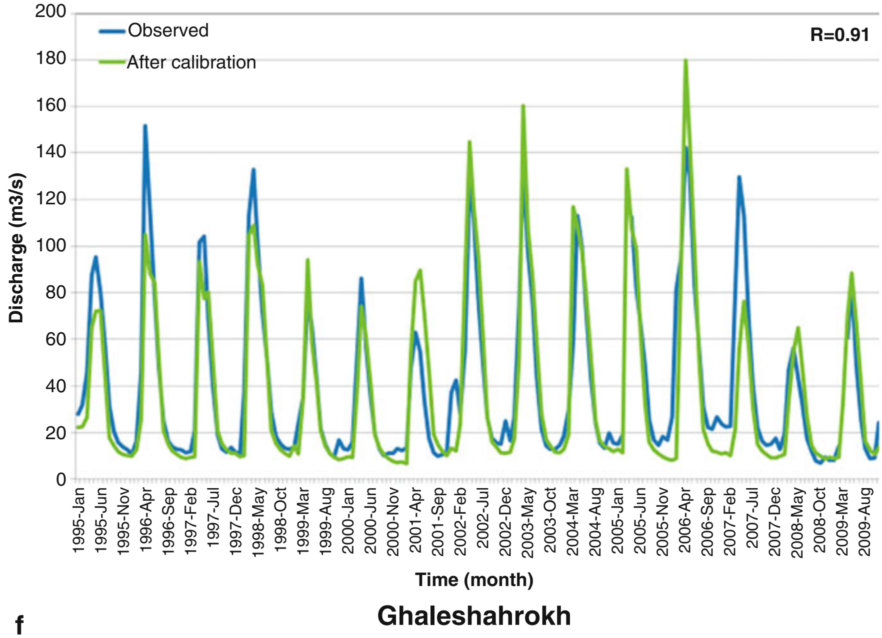

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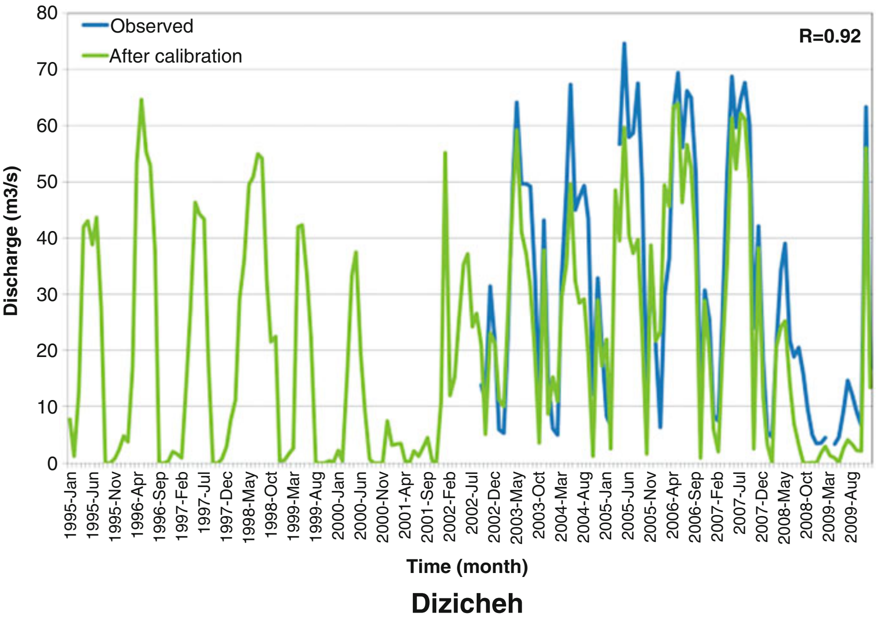

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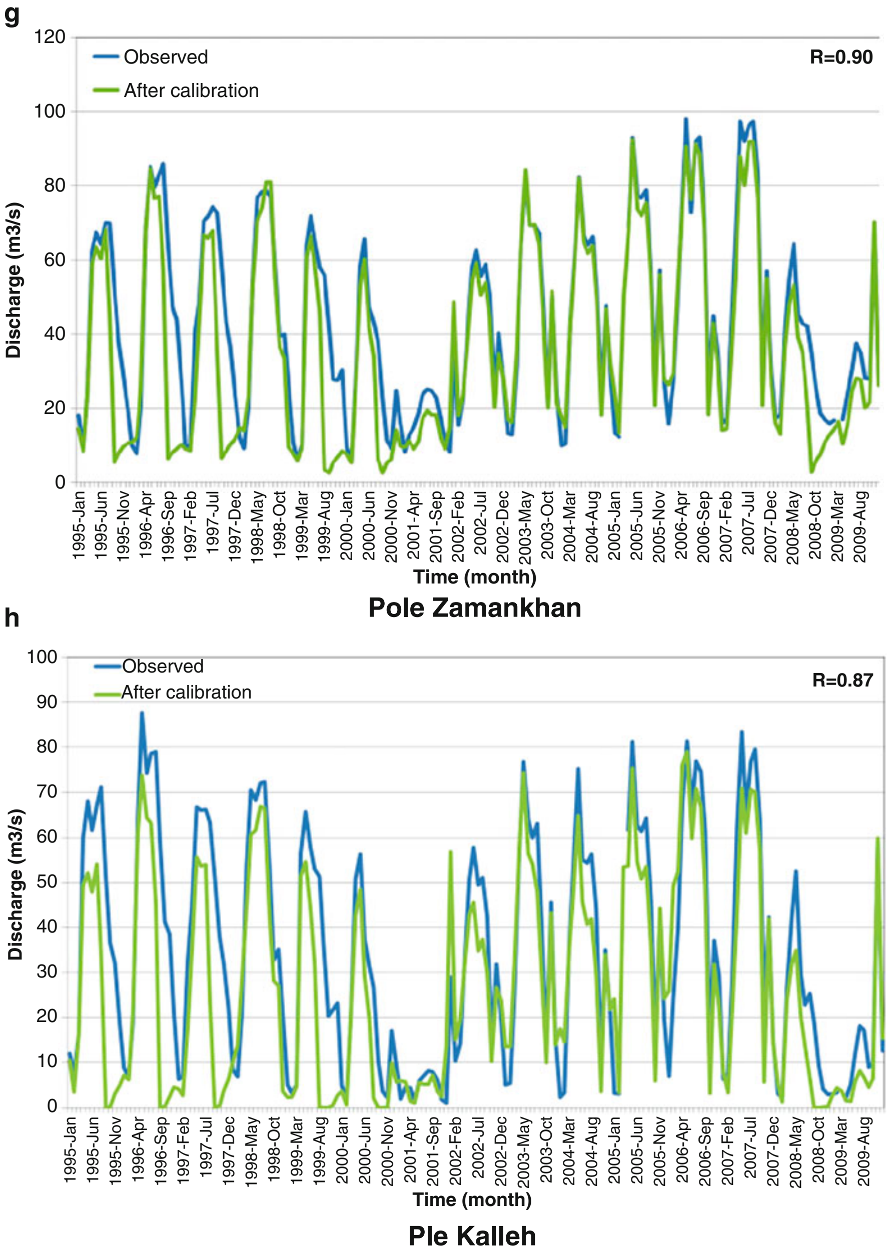

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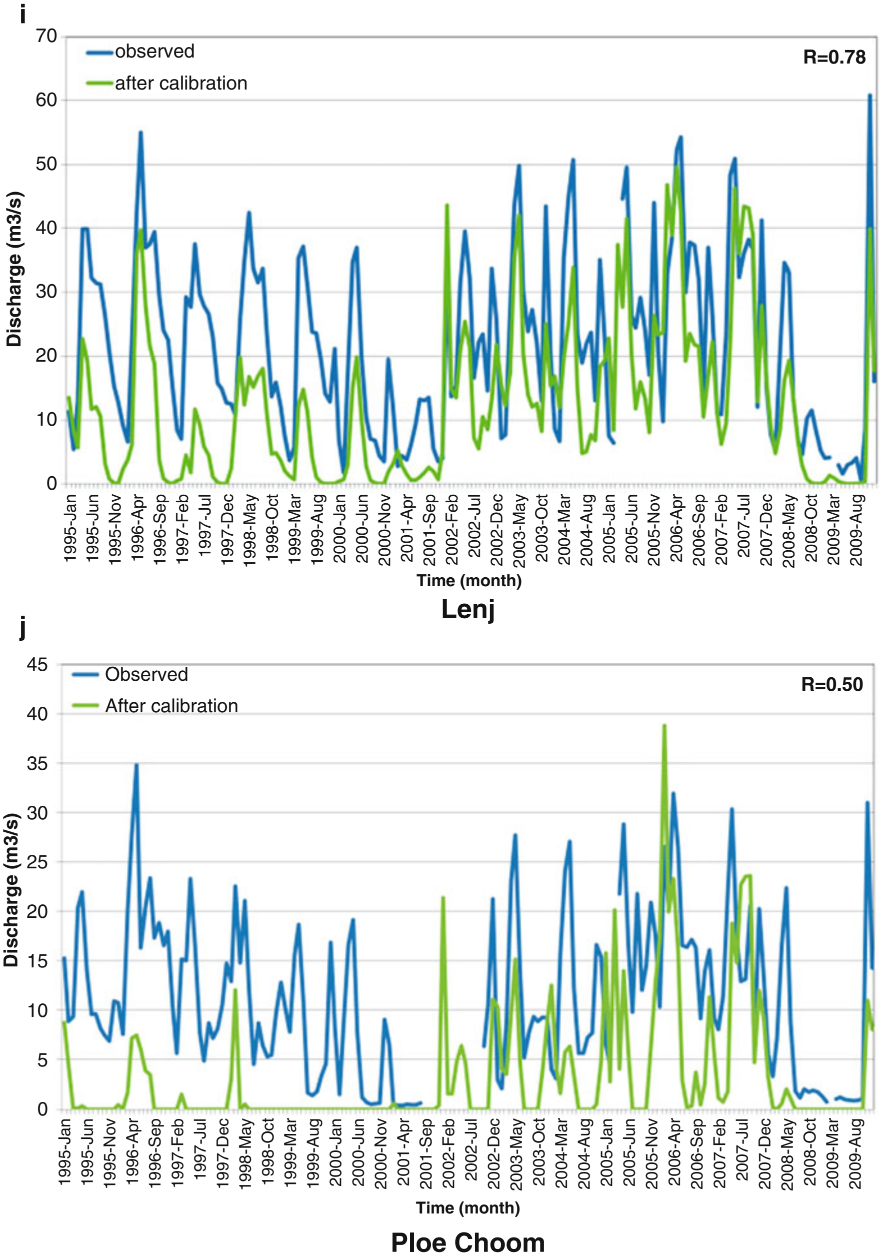


Fig. 7.4 (continued)

7.4.2 *Spatial and Temporal Changes of Water Resources Components*

7.4.2.1 Precipitation (PCP)

The spatial variations of precipitation in the ZRRB during the four studied periods are depicted in Fig. 7.5. As shown, the northern and high-altitude areas in the west received much higher precipitation (about 300–1500 mm/year^{-1}) than the middle and eastern parts of the basin (in most parts less than 150 mm/year^{-1}). In addition, the investigation of the temporal variation of PCP during the different various periods shows that the middle and eastern parts of the basin are more affected by PCP variations than the western parts. The main reason for providing the precipitation simulation results in the current study is to accurately investigate its impact and contribution to the changes of each water component (i.e., BW, GWF, and GWS). Furthermore, the temporal variations of PCP along with BW, GWF, and GWS are reported over the four investigated periods (annual averages) in order to better understand the changes in the water resource components in the catchment area.

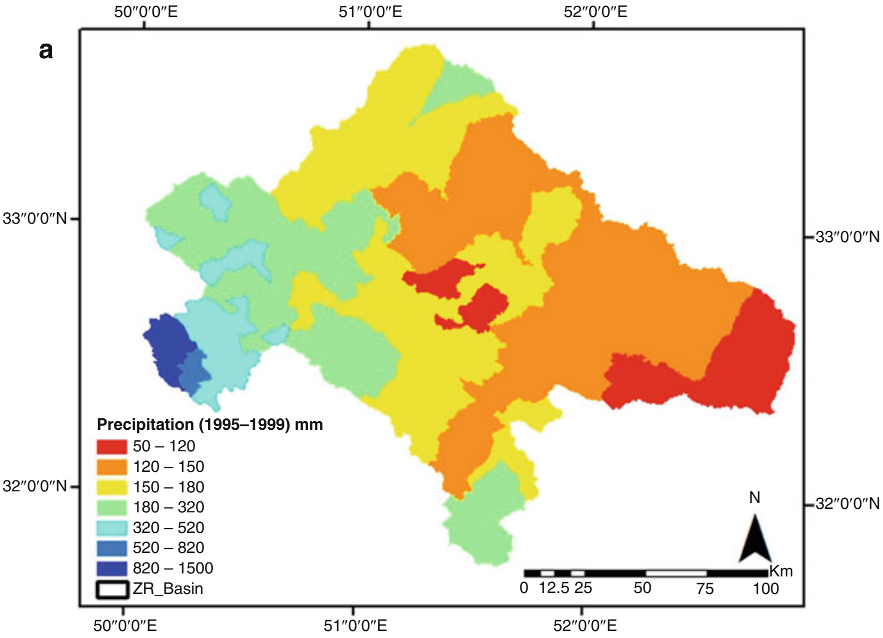
7.4.2.2 Blue Water (BW)

The spatial variations in the blue water resources in the Zayandeh Rud river basin during the four studied periods were directly dependent on spatial changes in precipitation in the basin (Fig. 7.6). In all the studied periods, the highest BW values were observed in high-altitude areas upstream of the dam. The spatial and temporal changes of the blue water resources in the eastern and central parts were negligible. In most sub-basins downstream of the basin, less than 10 mm/year^{-1} blue water has been generated in all four investigated periods.

In order to better understand changes in the availabilities of fresh water resources (i.e., blue water) in the basin as well as to make the values more tangible, the long-term minimum, average, and maximum values of BW vs precipitation (in million cubic meters, MCM) during the four studied periods were calculated and are depicted in Fig. 7.7. The greatest long-term mean BW value (693 MCM year^{-1}) was observed during period 3 (2005–2009), while the worst conditions for access to fresh water resources (blue water) were seen during period 2010–2014. The lowest long-term average of precipitation (5296 MCM year^{-1}) was also simulated for the same period (i.e., 2010–2014).

7.4.2.3 Green Water Flow (GWF)

The highest GWF values were observed in western portions of the basin, parts of the study area that received more precipitation and thus more potential for evapotranspiration (Fig. 7.8). The mean annual actual evaporation (i.e., green water flow) in



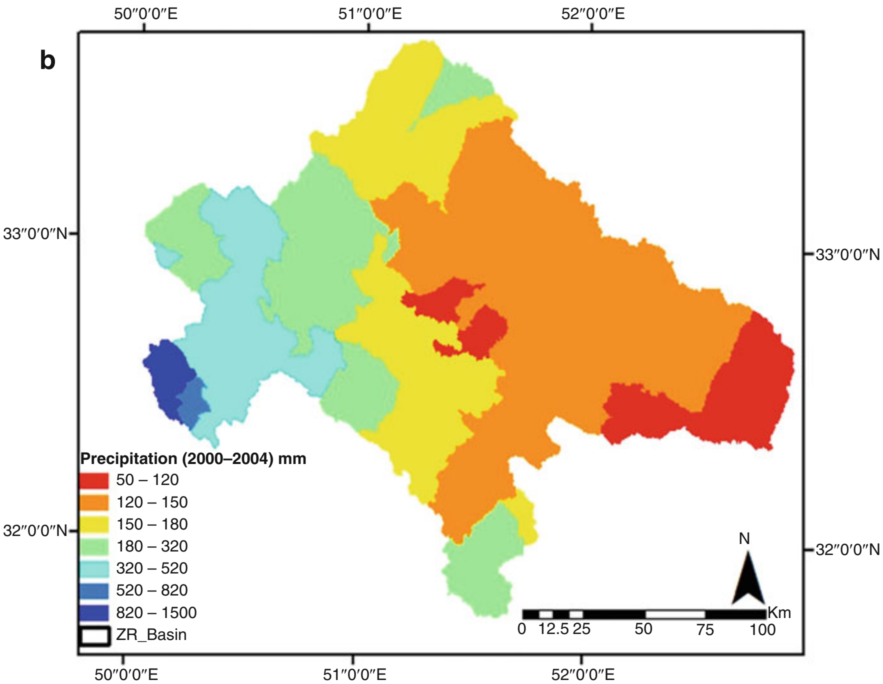


Fig. 7.5 Spatial variations of precipitation in Zayandeh Rud river basin during the four studied periods: (**a**) (1995–1999), (**b**) (2000–2004), (**c**) (2005–2009), and (**d**) (2010–2014)

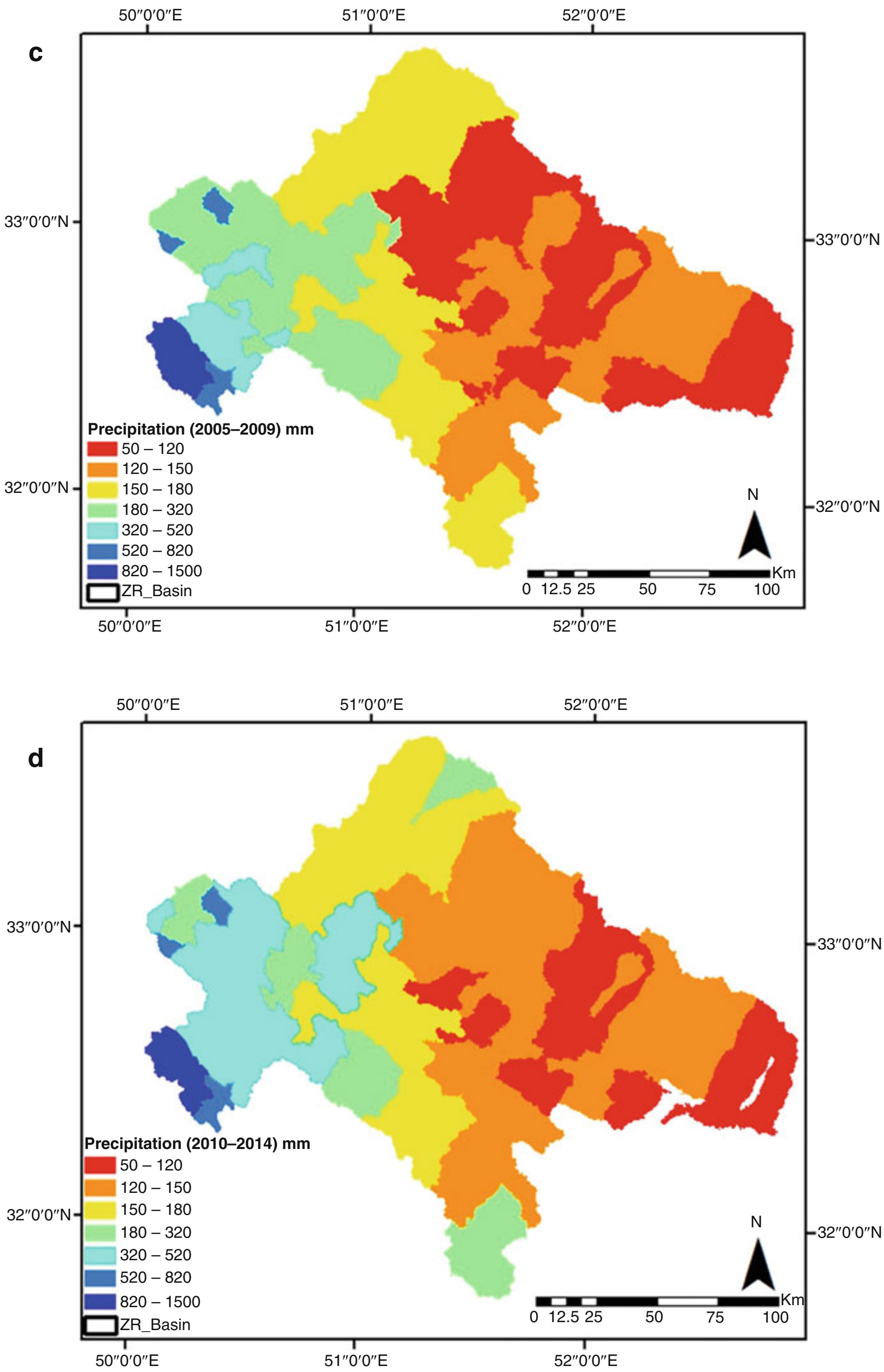


Fig. 7.5 (continued)

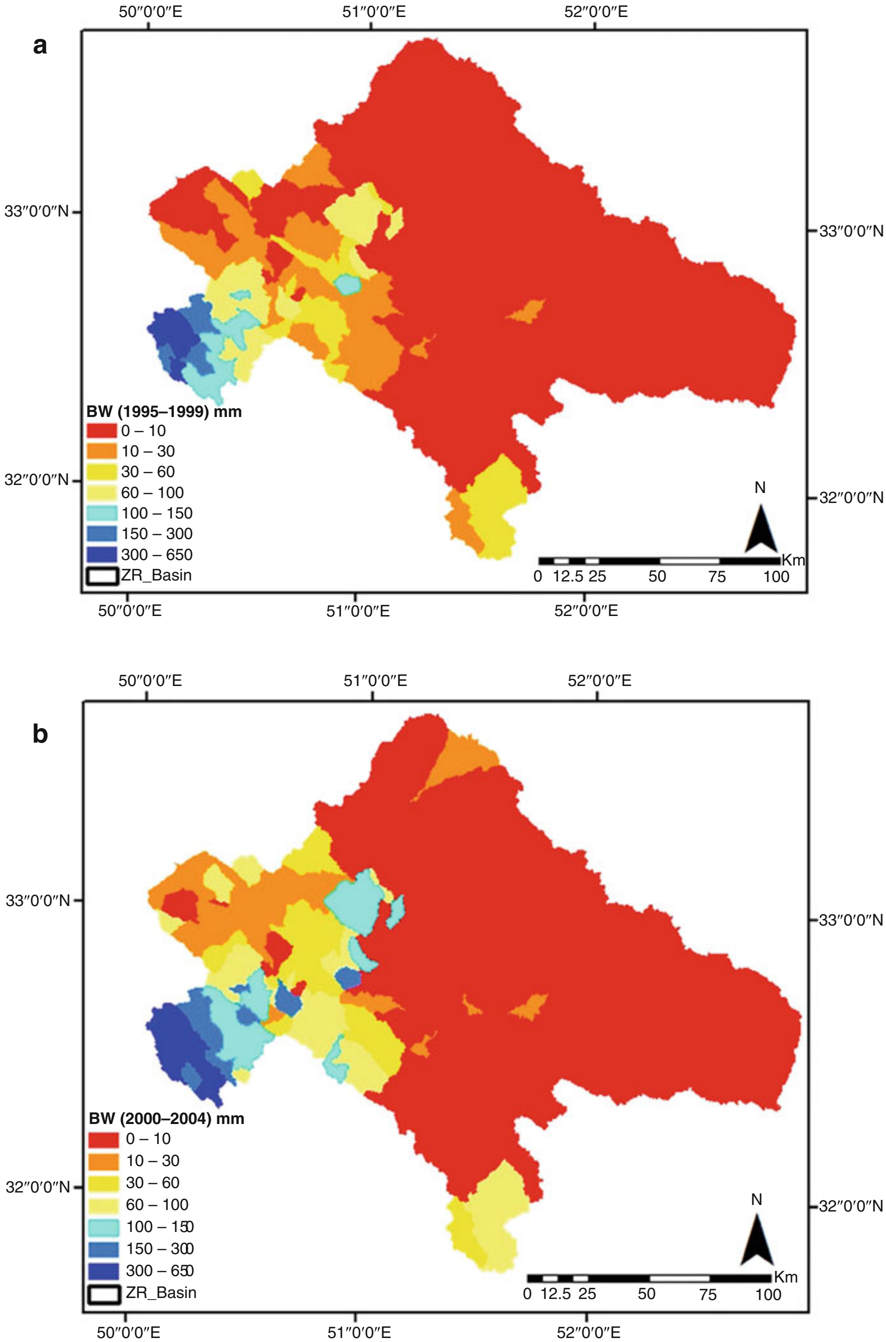
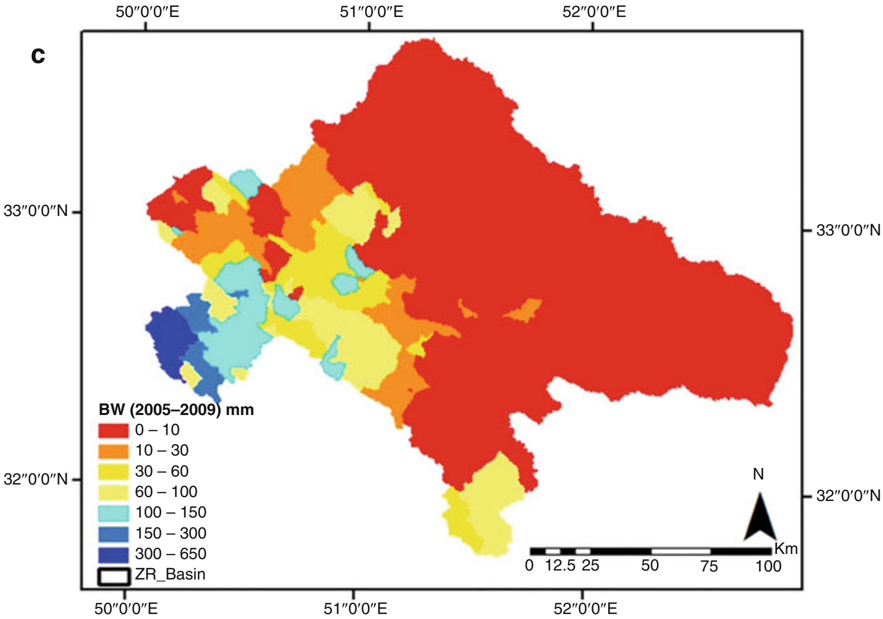


Fig. 7.6 Spatial variations of blue water in Zayandeh Rud river basin during the four studied periods: (**a**) (1995–1999), (**b**) (2000–2004), (**c**) (2005–2009), and (**d**) (2010–2014)



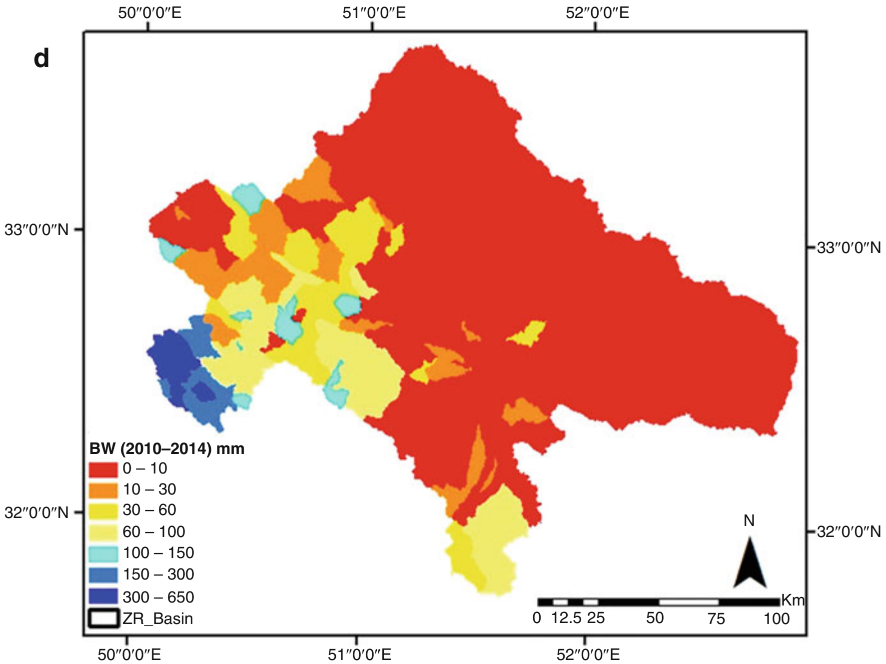


Fig. 7.6 (continued)

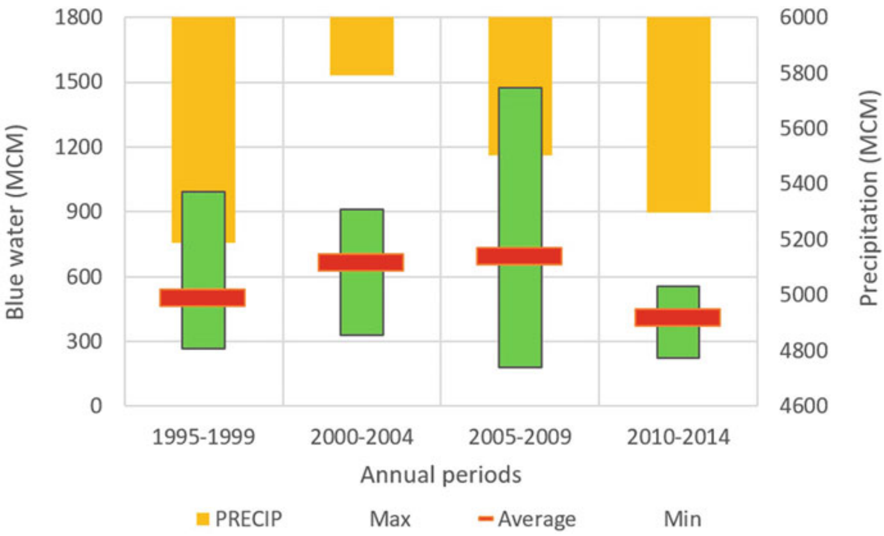


Fig. 7.7 Temporal variations of blue water vs precipitation (in million cubic meters, MCM) in Zayandeh Rud river basin during the four studied periods

most sub-basins upstream of the basin and in all four studied periods was more than 200 mm/year^{-1}. This is while in the eastern part of the region (especially the Roodasht area), the GWF is mostly lower than 160 mm/year^{-1}. Green water flow has an inverse relationship with potential evapotranspiration (PET), which may be due to the availability of water resources. The lack of sufficient water resources in the eastern parts of the basin seems to be the main reason for the lower evapotranspiration in these reaches in comparison with the sub-basins located in the western parts.

Comparison of long-term average values of GWF vs precipitation (in million cubic meters, MCM) during the four studied periods also revealed that the maximum mean annual green water flow (approximately 5440 mm/year^{-1}) was in the fourth studied period which has lower precipitation compared to the two previous 5-year periods (Fig. 7.9). Although the highest rainfall occurred in the second studied period (i.e., 2000–2004), the mean long-term value of green water flow was lower in this period than in the third and fourth periods. These findings suggest that the green water flow in the basin depends more on the availability of surface water and agricultural activities in the basin than on precipitation. However, the precipitation and its spatial and temporal distributions have a significant influence on the maximum or minimum evaporation rate in the basin.

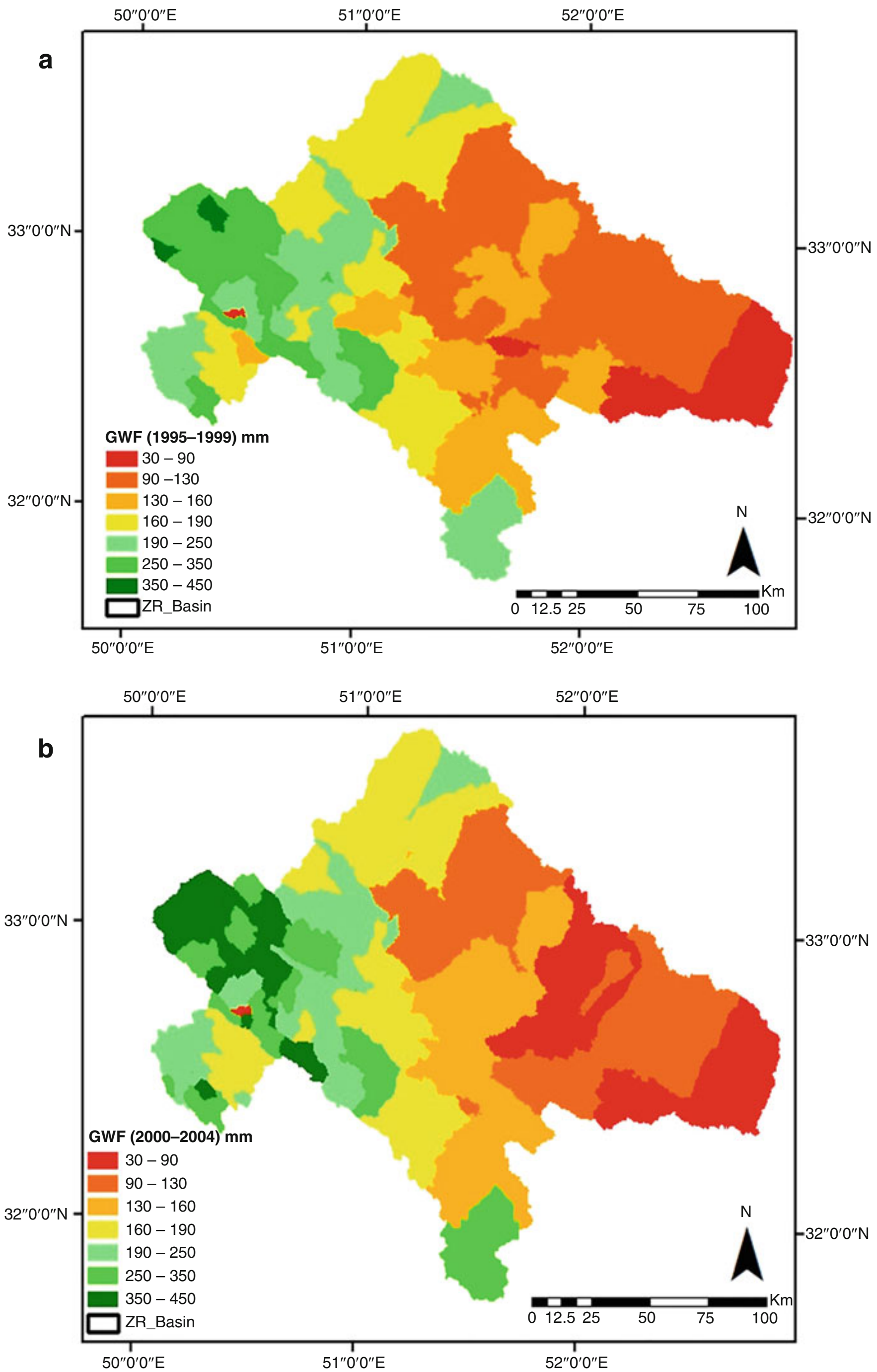
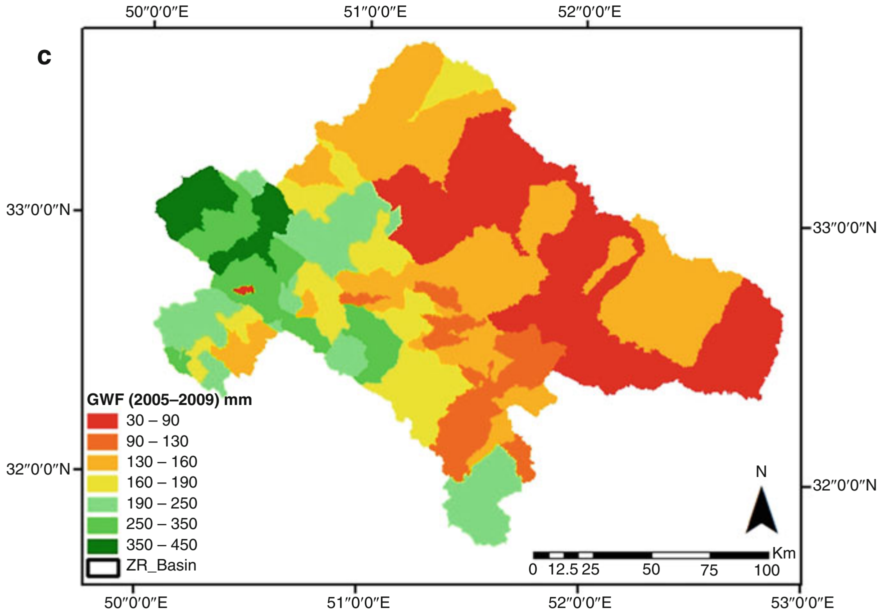


Fig. 7.8 Spatial variations of green water flow (GWF) in Zayandeh Rud river basin during the four studied periods: (**a**) (1995–1999), (**b**) (2000–2004), (**c**) (2005–2009), and (**d**) (2010–2014)



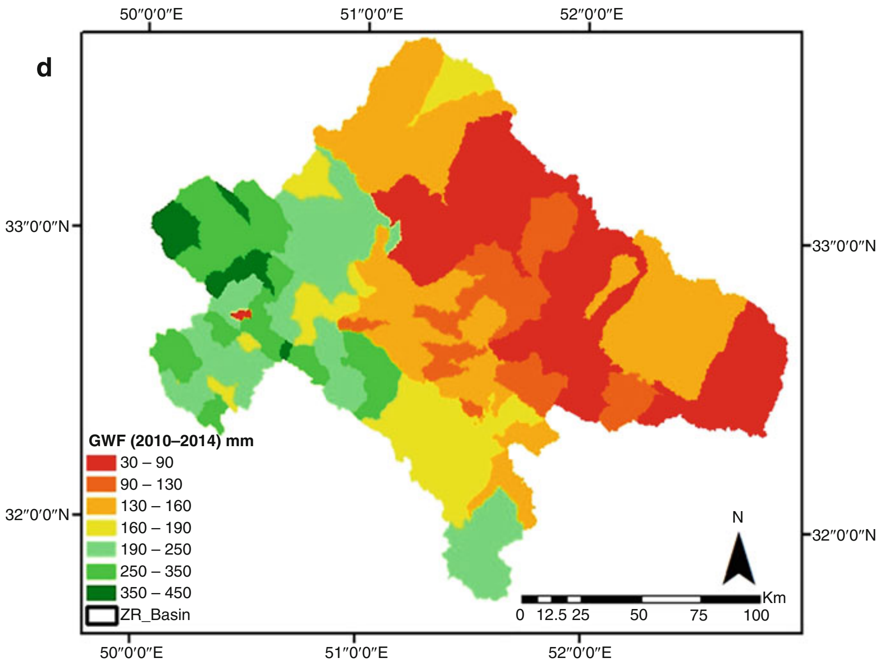


Fig. 7.8 (continued)

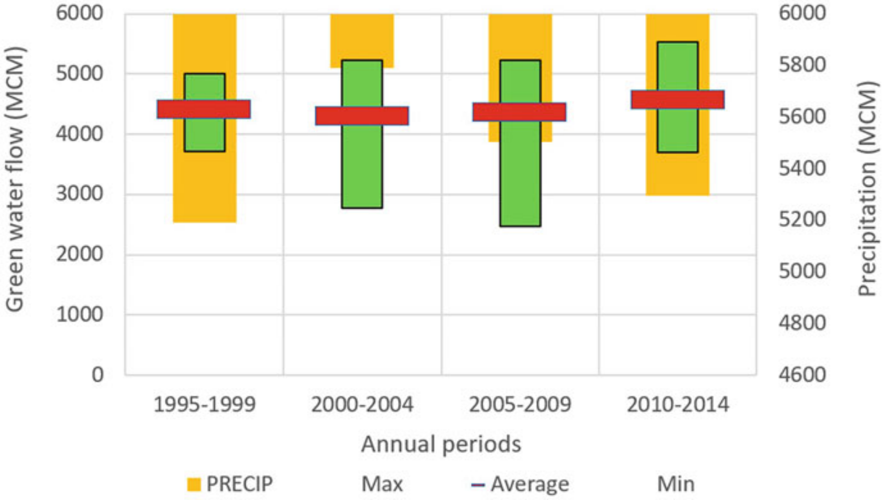


Fig. 7.9 Temporal variations of green water flow vs precipitation (in million cubic meters, MCM) in Zayandeh Rud river basin during the four studied periods

7.4.2.4 Green Water Storage (GWS)

Spatial variations of GWS in the Zayandeh Rud river basin during the four studied periods were more noticeable compared with other investigated parameters (Fig. 7.10). In the first study period (1995–2009), the amount of soil water storage (i.e., GWS) was much lower than in the other three studied periods, especially in the sub-basins of the eastern parts. The GWS values in most parts of the eastern sub-basins and in the northern parts of the study area were less than 30 mm per year^{-1}, possibly due to lower rainfall in this part of the basin compared to the other portions (especially upstream sub-basins, see Fig. 7.5). The green water storage component was greater than 50 mm per year^{-1} in most parts of the upstream dam during the period 4 (2010–2014). However, its long-term average value (in million cubic meters, MCM) during the second period (with the highest precipitation compared to the other periods) was greater than the fourth period (Fig. 7.11). The minimum simulated mean annual green water storage for the basin (about 843 mm per year^{-1}) was observed for the first 5 years of the study (period 1), the time span in which the lowest precipitation for the basin is simulated.

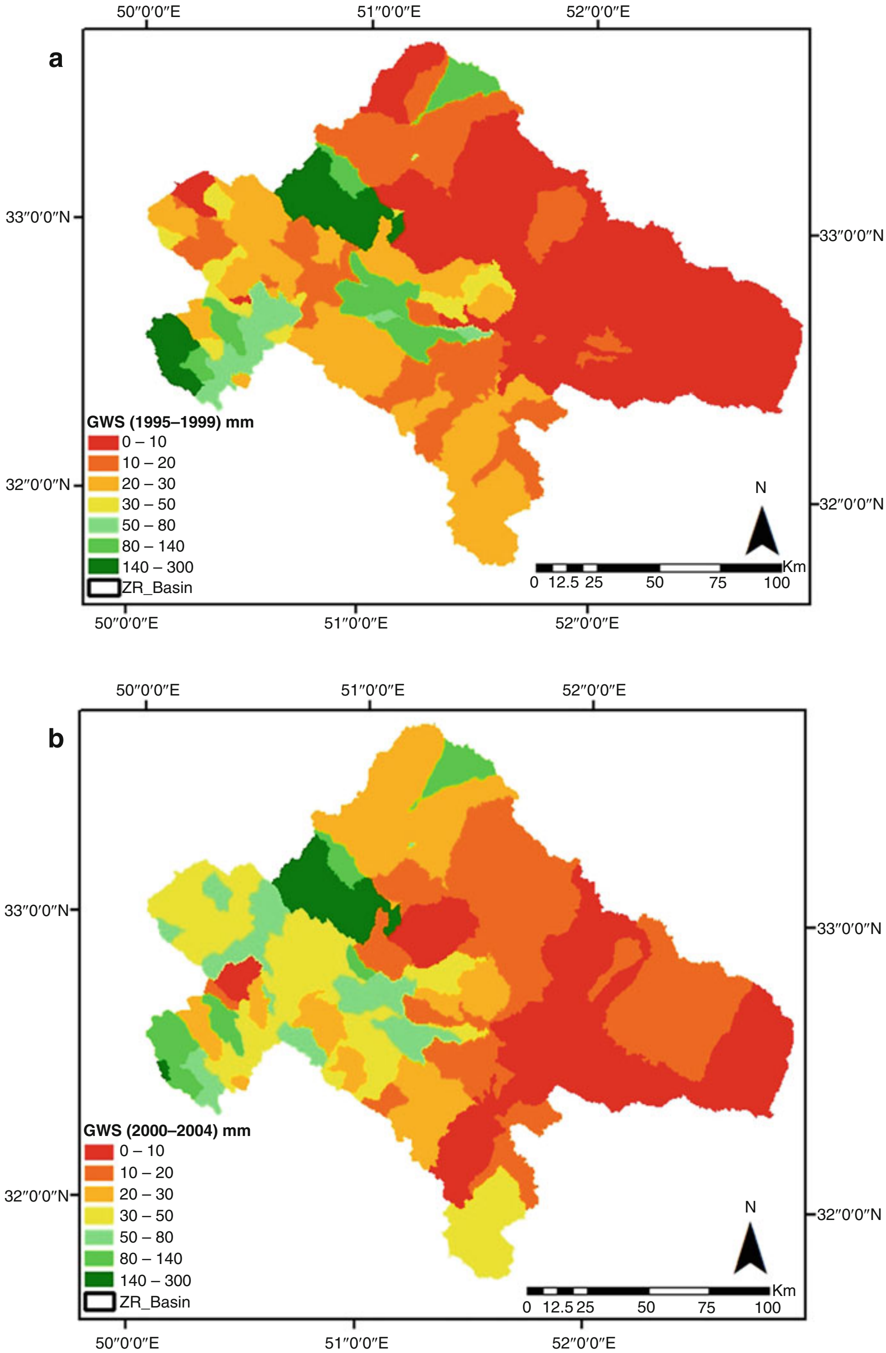


Fig. 7.10 Spatial variations of green water storage (GWS) in Zayandeh Rud river basin during the four studied periods: (**a**) (1995–1999), (**b**) (2000–2004), (**c**) (2005–2009), and (**d**) (2010–2014)

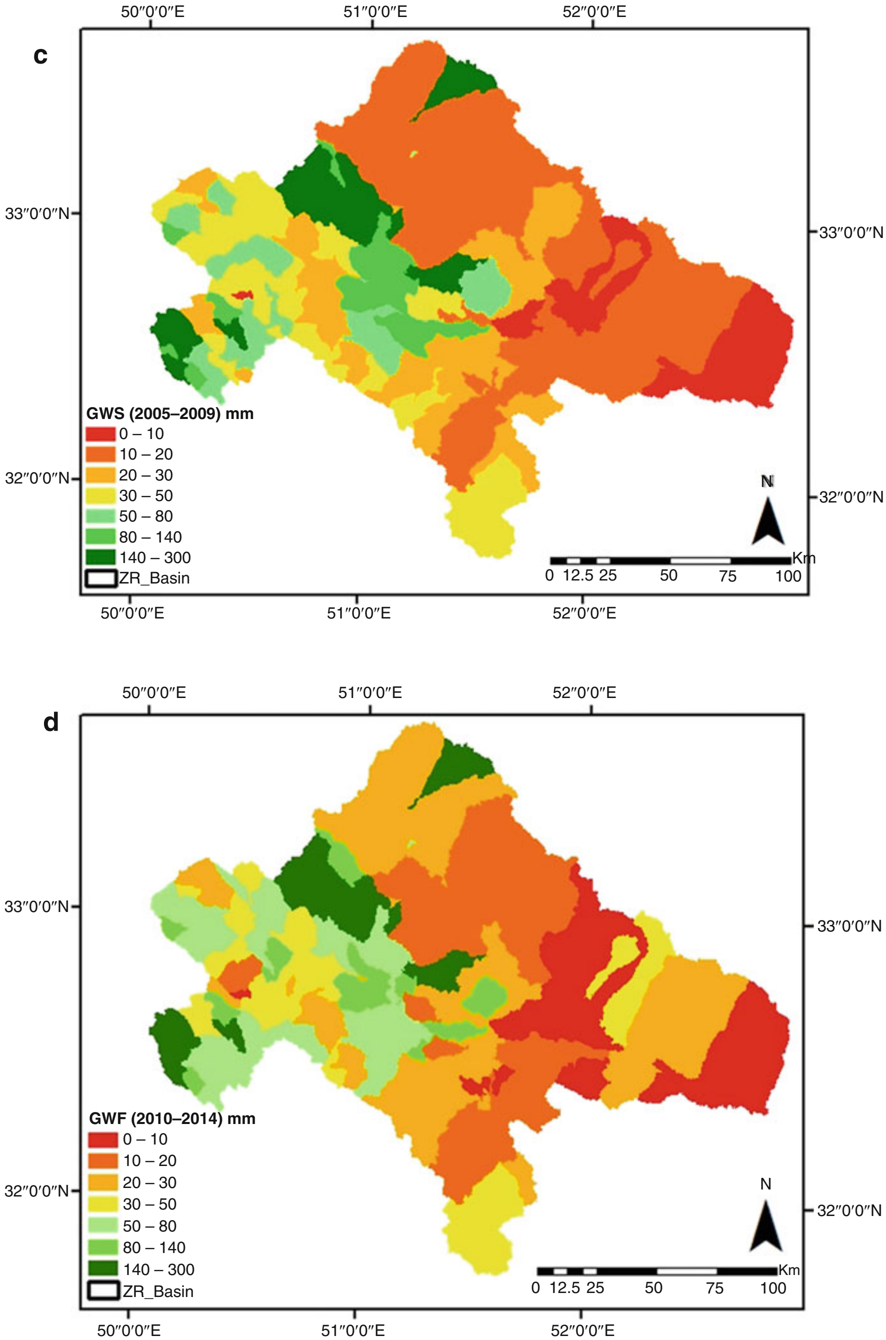


Fig. 7.10 (continued)

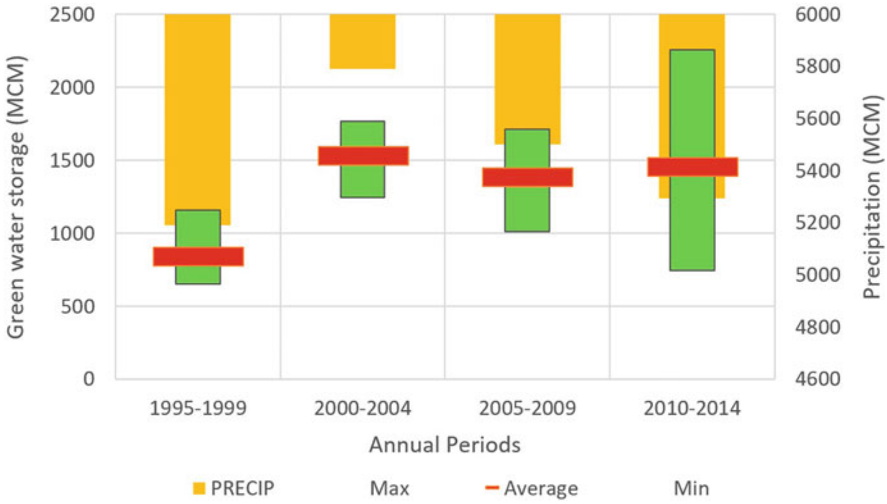


Fig. 7.11 Temporal variations of green water storage vs precipitation (in million cubic meters, MCM) in Zayandeh Rud river basin during the four studied periods

7.4.3 Monthly and Annual Changes of Water Resources Components

7.4.3.1 Monthly Changes

In order to investigate the monthly variations in water resources components (PCP, BW, GWF, and GWS) in the study area, the monthly averages of each component were calculated for each month of the year for the duration of the entire simulation period (20 years). In summer and early and mid-autumn (December and October), when the lowest PCP occurs in the basin, the smallest amount of BW was observed (Fig. 7.12). The highest amount of blue water resources was also simulated for March with an approximate value of 272 MCM. The highest precipitation value (965 MCM) in the basin happened in the same month in the basin.

From October to the end of April, green water flow (monthly average) rises in the basin and reaches its highest value in April (788 MCM). The increasing trend of GWF is proportional to the precipitation in the corresponding months. Then from May to the end of September, the amount of GWF decreases due to reduced PCP and reaches its lowest level in September (43 MCM).

Investigating the variations of green water storage during the year also showed that the changes of this hydrological component is proportional to the changes in the months of the year in different seasons. When rainfall begins in the basin in the middle of autumn (especially upstream of the dam), the amount of GWS increases, and in the spring by starting the growing season and the use of plants from soil moisture as well as increments in the evaporation from the surface, green water

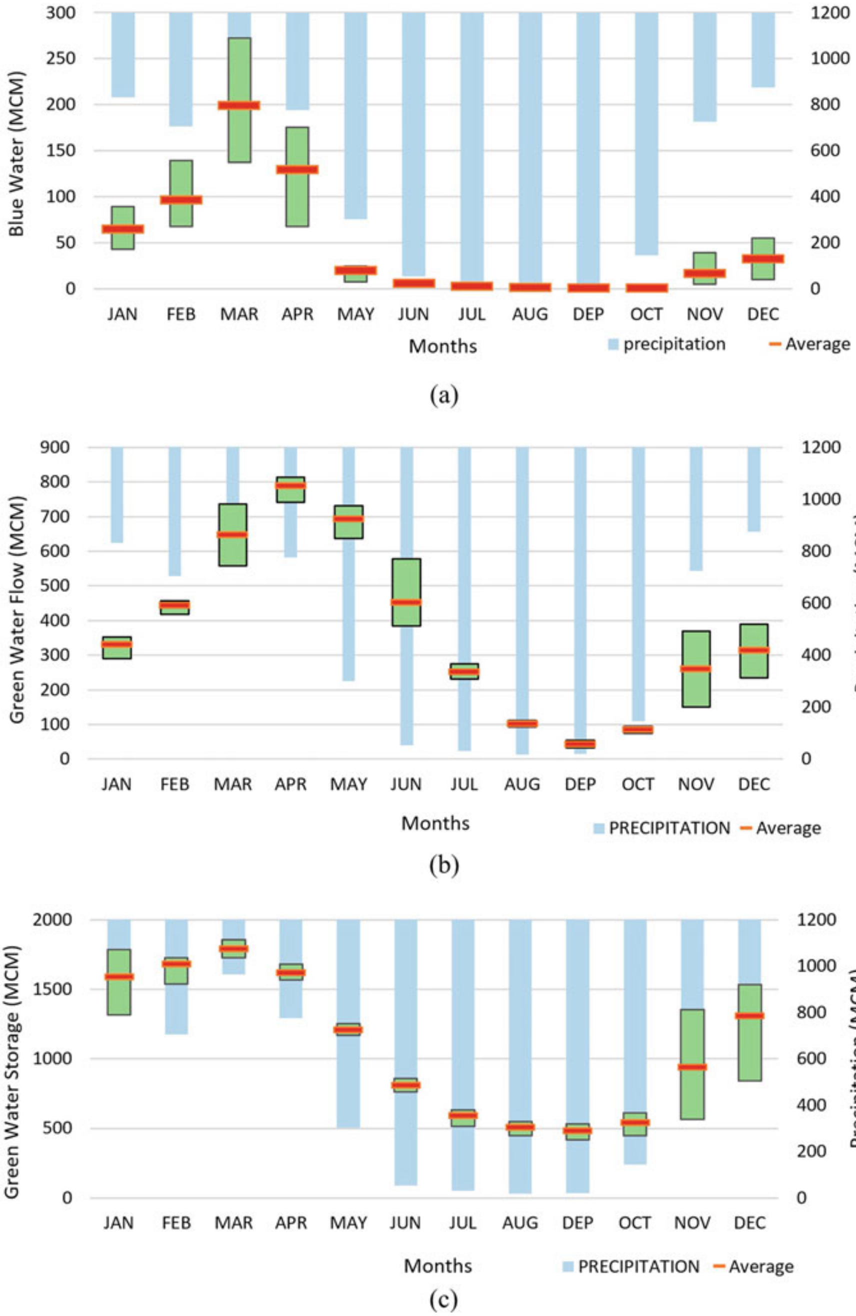


Fig. 7.12 Monthly variations in water resources components (BW, GWF, and GWS) vs precipitation in the study area for the entire simulation period (from 1995 to 2014)

storage begins to decrease. The lowest and highest GWS values were observed in September (480 MCM) and March (1788 MCM), respectively.

7.4.3.2 Yearly Changes

The annual changes of BW, GWF, and GWS components vs precipitation in the study area in each year from 1995 to 2014 are illustrated in Fig. 7.13. The results show that variations in the blue and green water resources in the basin are highly dependent on PCP changes in the area. In general, increased precipitation over different years resulted in higher amounts of studied water resources components. For instance, the highest BW value during the studied period (1475 MCM) was observed in 2006 when the maximum mean annual precipitation (1475 MCM) was simulated. For the GWF component, the maximum and minimum values occurred in 2014 and 2008 (5540 and 2473 MCM, respectively), and the highest GWS value was observed in 2012 (2256 MCM).

On the other hand, investigating the trend lines of the parameters, especially blue water, shows that this hydrologic component had a rising trend from 1999 to 2006 and then a decreasing trend is observed (Fig. 7.13). The main possible reason for this finding might be the changes in surface water resources (especially river flow) over the years. However, green water storage changes are less likely to follow this trend as changes in soil moisture are mainly affected by precipitation, plant growth, and surface evapotranspiration.

7.5 Discussion

7.5.1 Calibration Improvement

The recalibration processes and employment of SWAT 2012 resulted in meaningful improvement in the simulation of river discharge in most of the hydrologic stations in comparison to the hitherto available SWAT-Zayandeh Rud version. The main reasons for improvement might be the use of SWAT 2012 which have more benefits than the SWAT 2009 version. In SWAT 2012, for instance, positron emission tomography and soil moisture routing, irrigation water from a reach, snow melt routing, and default value for sub-basin channel slope (CH_S1) from the mean sub-basin slope to the longest flow path slope are improved, which could result in a better simulation of river discharge, especially in mountainous river basins like the ZRRB. In addition, the new sensitivity analysis, and identifying the parameters that the model is sensitive to their changes (especially parameters related to precipitation like PCPMM, PCPSKW, and PCPSTD), was effective where some new sensitive parameters (particularly parameters related to precipitation and temperature) were determined and included.

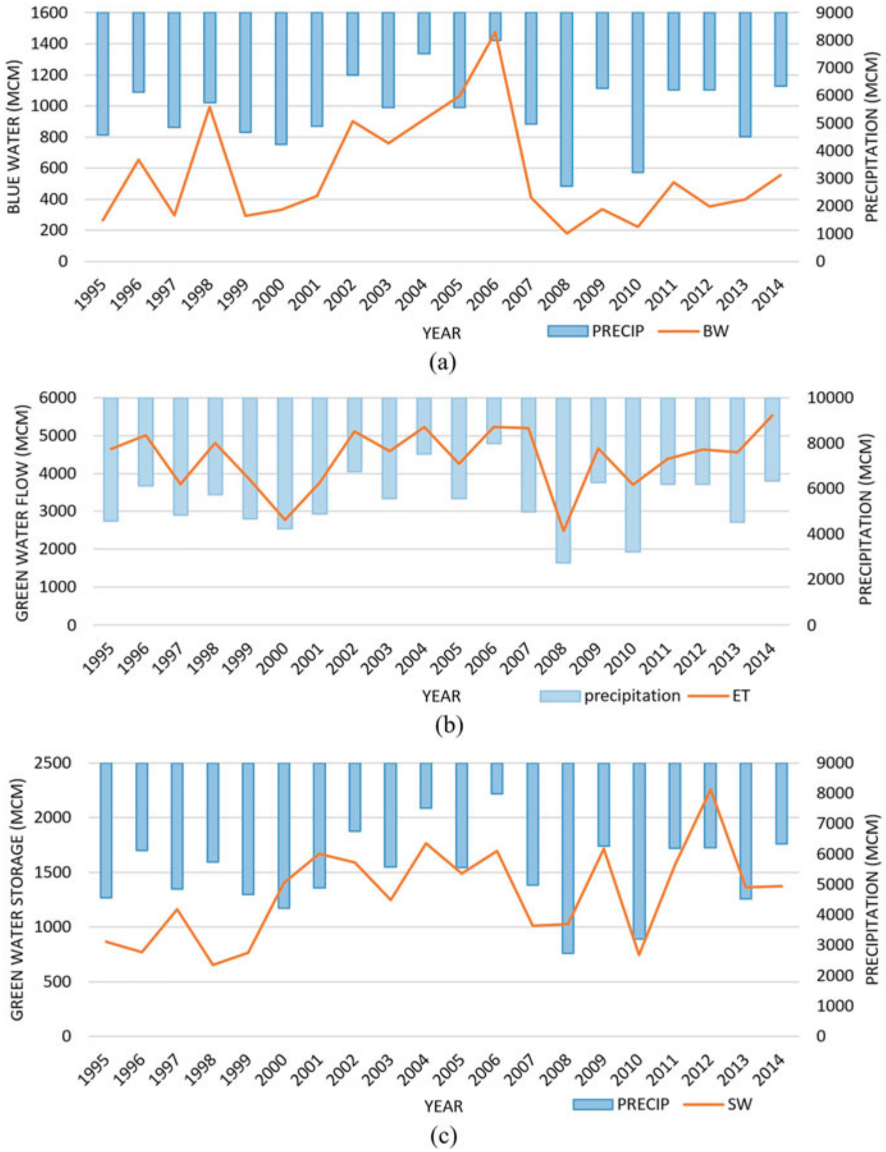


Fig. 7.13 Yearly changes in water resources components (BW, GWF, and GWS) vs precipitation in the study area for the entire simulation period (from 1995 to 2014)

Deployment of a larger number of hydrometric stations with observed data in the basin, especially in the upstream of the dam, also led to a better illustration of hydrological conditions in the basin and thus may have improved the calibration results. However, the simulations at some stations were not considerably improved due to the lack of data. In fact, the available data generally allowed obtaining more satisfactory results upstream in high-land terrain. However, the inclusion of a larger number of climate stations is needed to improve the quality of the predictions. On the other hand, in the downstream stations the calibration performance was highly dependent on the quality and quantity of water use and water diversion data which were rarely available. Therefore, data records for water uses and water diversion in this part of the basin with more and better quality and quantity is vital.

7.5.2 Spatial and Temporal Changes of Water Resources Components

Investigations of the spatial and temporal variations of water resources components in the basin resulted in different findings for various time spans as well as different parts of the study area. The blue water component, for instance, had higher values in the western parts of the basin than the eastern parts which might be due to the fact that the land uses in these areas are mainly forest and rangelands with a lot of rainfall and snowfall during the year. In the eastern part of the basin (Roodasht area), agricultural fields, poor rangelands, and desert are the dominant land uses with relatively low precipitation and thus little BW-resources. These characteristics cause water stress in the agricultural sector in these areas. The high values of BW in some parts of the southern sub-basins like Dashte Qomsheh and the areas close to the Zayandeh Rud dam might be due to the existence of agricultural lands and gardens (as the most surface water users in these areas) and relatively high amount of precipitation in these areas.

On the other hand, the long-term annual survey of BW-resources changes in the basin during the four studied periods revealed that the BW amount increased by about 33% from the first period to the second period and decreased by 41% from the third period to the fourth along with a 6% increase and 4% reduction in precipitation, respectively (Fig. 7.14). This finding shows that the Zayandeh Rud river basin encountered the best conditions in terms of rainfall and surface water resources availabilities during the second period and the worst conditions in the fourth period.

The presence of enough water resources and irrigated areas upstream of the basin caused a higher amount of evapotranspiration in these parts of the basin as compared to the eastern portions and thus greater values of green water flow (GWF). The central parts of the basin have also relatively higher GWF than the eastern parts. Most of the agricultural lands are located in the central and eastern parts of the basin, with a mean annual precipitation lower than 180 mm per year^{-1}. Irrigation operations are also extensively carried out in central areas in different seasons (especially in dry seasons) which led to a greater evapotranspiration rate (and thus GWF) in central sub-basins than the eastern parts of the basin. In other words, the lack of adequate water resources in the lower reaches of the basin (Roodasht) prevents evapotranspiration in comparison to the central and upper reaches. The eastern parts

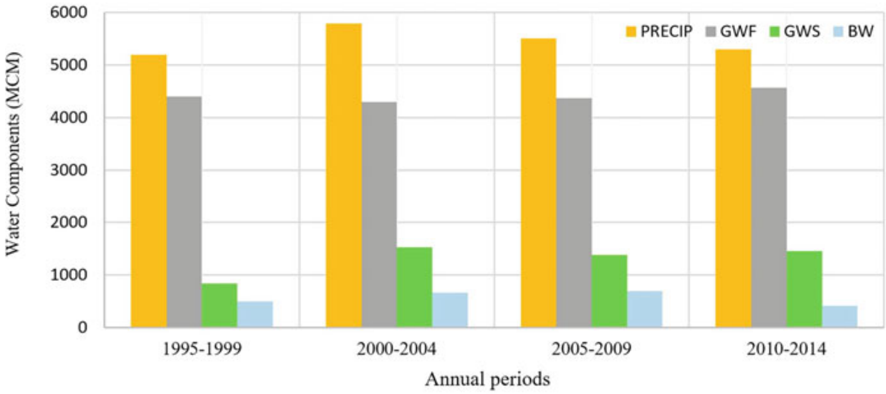


Fig. 7.14 Yearly averages of water resources components (BW, GWF, and GWS) vs precipitation in the study area for the four studied periods

of the basin have the lowest cumulative rainfall in the basin (mostly less than 150 mm per year^{-1}). In the western parts of the basin, the Boein Plains, Daran, Chehel Khaneh, and Damaneh have the highest GWF values, which might be due to the higher removal of groundwater resources for irrigation than other neighboring plains.

By comparing the simulation results for different investigated periods (i.e., temporal variations of GWF), the highest mean annual GWF value was observed for the fourth period, the period which had the lowest amount of mean annual precipitation, indicating that GWF is not dependent solely on precipitation as mentioned above (Fig. 7.14).

The existence of mixed agricultural lands, forests, and dense pastures in the western parts of the basin as well as having the highest amount of precipitation (see spatial distribution of precipitation in the basin in Fig. 7.5) seem to be the most important reasons for the high levels of soil water storage (i.e., green water storage, GWS) in the upstream sub-basins. Also, the low amount of GWS in the central parts of the basin can be due to differences in the type and characteristics of soil texture and land use in these areas compared with other parts. On the other hand, in the eastern part of the basin, and most parts of the northern sub-basins, relatively low GWS values were obtained. The main reasons might be the lower precipitation compared to the western parts of the basin, the presence of rainfed fields and urban communities, as well as the presence of shallow soil with poor vegetation cover in these areas. Different irrigation and agricultural managements, as well as the type of cultivated crops in different sectors, can also be a reason for the spatial variation of GWS in the basin. The highest amount of soil water storage was observed in the second period (2000–2004), the period that had the highest long-term average annual precipitation. This indicates that the amount of stored water in the soil depends, not only on agricultural management and activities but also the amount of precipitation.

7.6 Remarks and Recommendations

The results of this study demonstrate that the changes of water resources components (BW, GWF, and GWS) in the basin are influenced by spatial and temporal (monthly and annual) variations of climate parameters (particularly precipitation), agricultural management and activities, as well as soil and land use types. The changes of water resources components from the high-altitude areas upstream of the dam to the eastern parts of the basin were largely proportional to the variations of precipitation. The presence of irrigated areas in some parts of the basin also increased evapotranspiration and thus green water flow in those parts. On the other hand, the long-term averages of water resources components in different periods of investigated timespan show a significant decrease in precipitation and water availabilities as well as an increase in the green water flow from the second studied period (from 2005), indicating a more severe condition of the basin over the last 10 years of the simulation period. Blue water resources have a decreasing trend over the recent past years, green water flow conforms to an incremental trend, and green water storage shows upward and decreasing fluctuations.

Investigation of spatial and temporal changes of water resources components is exceedingly informative and helpful for the long-term planning of water resources and land use management. Awareness of these changes can help to make the right decisions for water resources operations, proper management of agricultural lands, and selection of appropriate time for cultivation and irrigation (especially in rainfed farming). In order to fully achieve these objectives and to complete the current study, it is therefore strongly recommended to investigate the climate change impacts on water resources components at different periods in the Zayandeh Rud basin. In addition, since the Zayandeh Rud river basin is located in semi-arid regions of Iran and thus green water storage (soil moisture) is an important source of water for rainfed farming, it is proposed to study and analyze the water footprints based on the concepts of scarcity and vulnerability of water resources in the Basin in the past, present, and future years.

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Part III
Water and Land Use Challenges in the Roodasht Region

Chapter 8
Realizing the Dynamic of Water Scarcity, Land-Use Change and Environmental Degradation in Roodasht, Iran

Wolf Raber, Mohammad Naser Reyhani, and Shahrooz Mohajeri

Contents

8.1 Introduction

The Zayandeh Rud in central Iran is one of the country's most important rivers, providing water for more than 4.5 million inhabitants. Originating in the Zāgros Mountains, the river passes through big agricultural areas, large-scale industrial sites

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and the city of Isfahan, before it ends in the Gavkhuni wetland, an area listed by the Ramsar Convention on Wetlands. The special geostrategic location of the Zayandeh Rud basin has been the driving force for socio-economic development with flourishing urban growth, a thriving industrial development and expanding agricultural areas. During the past decades, agricultural areas have been expanded by upgrading the water infrastructure and by modernizing the irrigation methods. Besides, big water intensive industries have been established in the basin. Along with increasing irrigation and industrial consumption, the demand for drinking water has increased dramatically. These parallel developments have led to an extraordinary increase of water users and water demand in the basin, backed by the distribution of legal water entitlements of the government challenging historic water distribution rationale (Raber et al. 2018).

Next to the increase in water demand, the region suffers from climate change characterized by global warming, less precipitation and higher climate variability (Eslamian et al. 2017). The water resources of the Zayandeh Rud have not been able to meet the demand of all stakeholders in the basin in recent years. The responses to this situation have been technocratic in nature, altering the natural hydrology of the region: The government has increased control over scarce water resources by building the central dam and extracting more water from other basins, and water users have increased their water availability by intense exploitation of groundwater resources (Raber et al. 2017). This puts high pressure not only on the environment by changes in land use, land degradation and desertification but in the long-term also on the water users themselves. The Roodasht region in the eastern part of the basin is one of the areas where these socio-economic and environmental issues have exacerbated dramatically. Roodasht is located in Isfahan County with a population of 52,000 people where most (approx. 12,500 active farmers) live from agriculture. People live in 8800 households inhabiting about 50 small towns and villages. Modern irrigation systems (Abshar and Roodasht network) were built to increase agricultural production which reached to around 70,000 ha in years with sufficient water resources (data source: Isfahan Water Board Company). Together with the Gavkhuni wetland, the Roodasht irrigation network is the tail-end of the Zayandeh Rud Basin and is therefore highly affected by water scarcity, water user conflicts and poor management of water resources (Molle and Mamanpoush 2012).

This chapter presents an overview on the complexity of water availability, land-use change and environmental degradation in the Roodasht region according to the findings of a vulnerability analysis of farmers towards water scarcity in the Roodasht area. The study was conducted within the research project on “Feasible Adaptation Strategies for a Sustainable Land Use in the Lower Reaches of the Zayandeh Rud River”. Information presented in this chapter draws on the findings of the project generated by exhaustive analysis of data from local institutions (water, environmental and agricultural authorities), on-site farmer interviews and expert workshops and interviews as depicted in detail in Raber et al. (2018). The chapter has a particular focus on the water availability and its impacts on and relation to the region.

In the following section, we present the current and past status of water availability and distribution in the basin and specifically the Roodasht region that has been affected by climate variabilities, surface and groundwater extractions, water rights and subject to decision-making processes on water management. Later, we discuss the environmental degradation and land-use change in the Roodasht region as a direct consequence of mismanagement and excess demand of water resources in the entire basin. In this section, we analyse how the water availability is interconnected with land-use conditions and environmental degradation in Roodasht.

8.2 Water Availability and Management in Roodasht

Eslamian et al. (2017) project a continuous trend of the variance in precipitation and higher temperatures in the Zayandeh Rud basin experienced in the past decade as effects of climate variability and climate change. These conditions lead to increased water demand and competition for water on the one hand and on the other hand to less available surface water in the Zayandeh Rud basin. Data of the Isfahan Regional Water Company show the effect of basin wide water scarcity by a drop of over 40% of water stock in the central Zayandeh Rud dam between the years 2007 and 2015. Water entitlements in the basin have become so complex and opaque that farmers in Roodasht feel illegitimately deprived of their water rights by decision-makers, which leads to a perception of exclusion and fraud causing social conflicts, with protests and fading trust in governmental institutions (Raber et al. 2018). In the following sub-sections, these aspects are presented in more detail.

8.2.1 *Climate Variability and Drought*

Climate change and variability, coupled with increasing water demand, is expected to intensify the current water scarcity in the basin particularly stressing agriculture and the environment. Research predicts a 0.6–1.1 °C increase in average temperature and a change in annual precipitation from −0.53 to +0.42% during the near-term future (2015–2044). The maximum and minimum temperature increases occur in summer (September) and winter (January), respectively. January, February and March are found to have the maximum precipitation decrease in comparison with other months whereas between October and November, a relative increase in precipitation is expected (Eslamian et al. 2017).

In the past decade, the whole catchment has experienced strong variance in natural precipitation but not quite as keenly as in the area around Roodasht. The combination of rainfall deficiency and high temperature in Roodasht creates a serious risk of drought when there is no distributed surface water to supply the water requirements of cultivated crops. In order to investigate the rainfall variance and deficiency in the region, the Standardized Precipitation Index (SPI) has been computed for the Varzaneh climatology station (52° 37′ E, 32° 24’ N) in Roodasht for the 12 month time scale covering 1968–2014. The results showed that the region faced severe to extreme droughts in the years 2001, 2008 and 2011. However during the past decade, more wet years have been recorded than dry years (Raber et al. 2018).

Generally speaking, climate change and drought are factors that exacerbate water-scarce conditions in the basin and Roodasht, caused by poor management decisions. According to the Coordinating Council for Integrated Management of the Zayandeh Rud Basin, the Zayandeh Rud basin is facing water shortages even in a climatically normal year.

8.2.2 *Surface Water Availability and Distribution in Roodasht*

Access to surface water is determined by water diversion to the Roodasht irrigation network, which is mainly decided on by the Coordinating Council for Integrated Management of the Zayandeh Rud Basin, dependent upon water stocked in the Zayandeh Rud dam and other criteria. Figure 8.1 shows the amount of available water in the dam and water diverted to the Roodasht irrigation network in the period between 2006 and 2015. The data show that parallel to a downward trend of the water stock in the dam, surface water division to the Roodasht irrigation network is

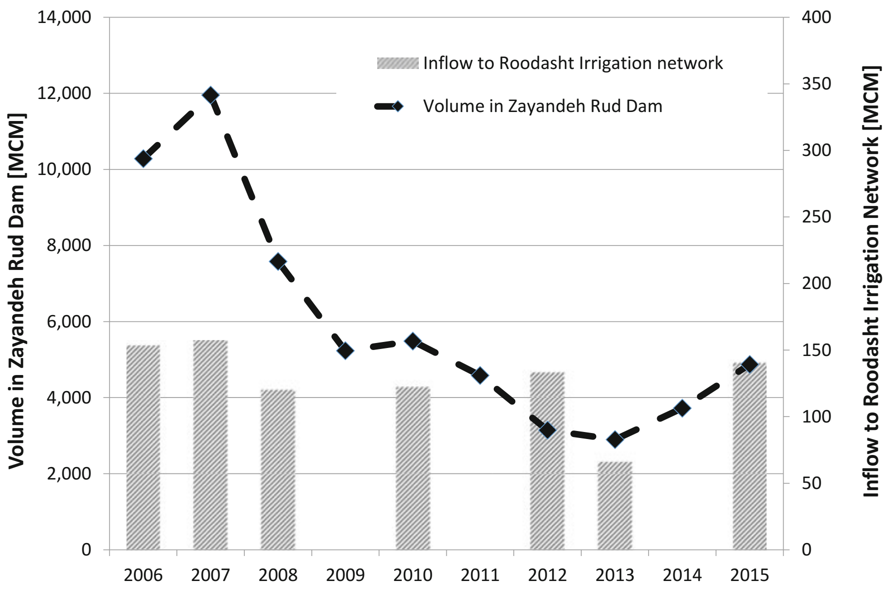

Fig. 8.1 Time series on annual water stock in the Zayandeh Rud dam and water supply to Roodasht irrigation network (data source: Isfahan Regional Water Company)

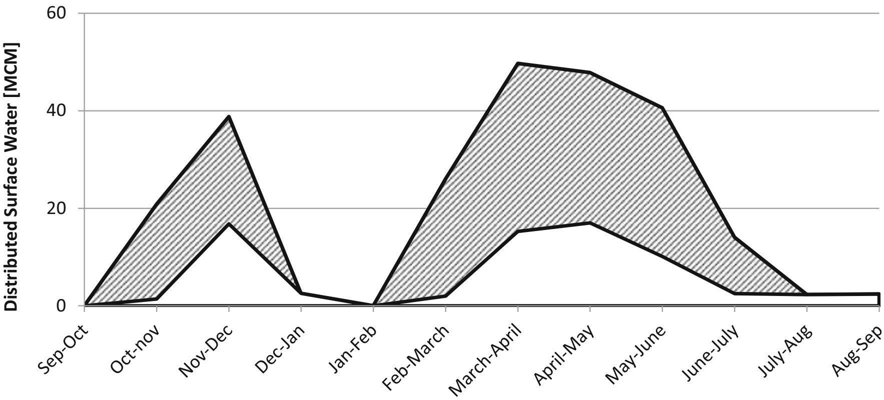

Fig. 8.2 Monthly range of surface water diverted to the Roodasht irrigation network (2005–2015) (data source: Isfahan Regional Water Company)

decreasing and shows strong fluctuations with several dry years with no water supply at all.

Surface water access through the irrigation network varies significantly in time and volume. Due to declining stocks in the central Zayandeh Rud dam and decision-making, access to surface water has decreased during the years. Uncertainty about irrigation water availability and no control over seasonal (temporal) access to surface water are major restrictions to the future development of the agricultural sector in the region. Data of the Isfahan Regional Water Company on long-term development of the surface water distribution to the downstream region of the Zayandeh Rud from 1992 to 2012 shows that diversion of surface water to Roodasht has decreased by almost 50%. The environmental flow discharged into the Gavkhuni wetland measured close to Varzaneh has decreased by as much as 90%. Access to irrigation water resources can be distinguished from access to surface water and access to other water sources, particularly groundwater. Farmers in Roodasht mainly use both of these water sources. Furthermore, natural precipitation plays an important role for farmers for sustaining crops in between two irrigation periods. Nevertheless, rainwater harvesting is not practised by farmers in the region due to low annual precipitation (Raber 2017; Raber et al. 2017).

Regarding the timing of irrigation water availability, data from the Isfahan Regional Water Company shows that water is usually diverted to the Roodasht irrigation network during two time periods: between October and December, as well as between March and June, whereas the later period has an overall higher water donation level (see Fig. 8.2).

Most farmers are entitled to receive a temporal share of irrigation water (time) from the network according to the Sheikh Bahaei (HAGHABE) share principle. The little control on timing of water access in the irrigation network is a major restriction for improving irrigation efficiency and crop choice (Raber et al. 2018).

8.2.3 Groundwater Extraction

Groundwater access is a key factor for irrigation water control and resilience to drought. Most farmers were used to apply junctive irrigation by groundwater and surface water. But groundwater quality and availability has decreased strongly in the past decades due to overextraction and limited recharge, which imply the risk of salinization of soils and reduced agricultural productivity.

Due to water scarcity, groundwater tables have declined and water quality downgraded severely in the past years, particularly for shallow wells. In general, groundwater access allows farming for a period of time independently of availability of surface water in the irrigation network, although farmers report that groundwater has been becoming too saline (with extreme values of up to 20 dS/m) in recent years to be used as the only source of irrigation water. Apparently deep wells with >100 m depth have less problems with salinity than shallow (semi-deep) wells of <20 m depth. In most cases farmers have to balance surface and groundwater irrigation based on their experience and by regularly testing salinity of groundwater (Raber et al. 2018).

Regarding Fig. 8.3, one can see where, particularly in the region around Varzaneh, the largest amount of approx. 8000 official agricultural wells in Roodasht (state 2011) are located (experts report high numbers of illegal wells in Roodasht). The figure also shows that around 98% of the identified wells are between 4 and 20 m deep, whereas only about 100 wells are up to 100 m deep and just 40 of them are deeper than 100 m. The abundance of a vast number of shallow wells supports the statement by experts that aquifers in the region are shallow and thin, meaning that they can usually be tapped easily, but are also highly reactive towards recharge, depletion and salinization.

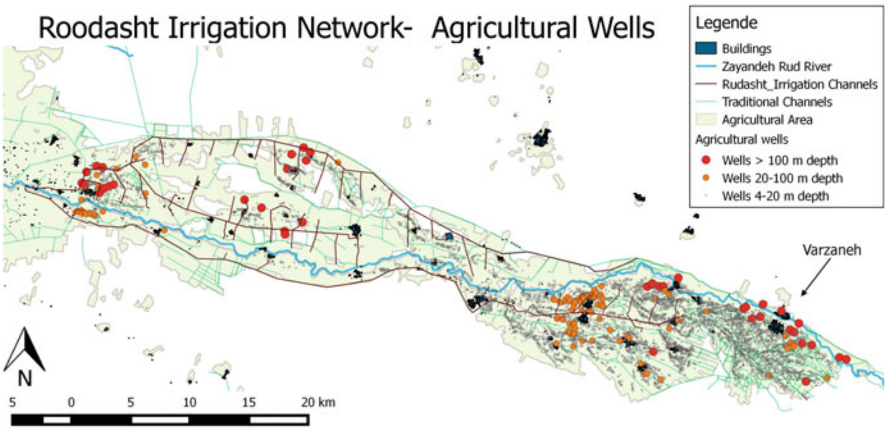

Fig. 8.3 Roodasht irrigation network with official agricultural wells (data source: Isfahan Regional Water Company, 2011)

Groundwater recharge is furthermore facilitated by (1) water flowing through the natural river bed of the Zayandeh Rud, (2) percolating irrigation water by water flowing though earthen secondary and tertiary irrigation channels (apparent in Varzaneh region) and irrigation and application of "inefficient" irrigation methods as well as (3) natural precipitation in the area. Since most of the mentioned factors are reduced by the limited amount of surface water diverted to the downstream area of the Zayandeh Rud during the past water-scarce decade, groundwater tables are declining, which is further intensified by heavy groundwater extraction for agricultural purposes. The described groundwater dynamics in relation to recharge and abstraction in the Zayandeh Rud basin is also confirmed by literature (Molle et al. 2009).

To sum up, decreased access to irrigation water through the irrigation network is a threat for agricultural production, increases uncertainty of future development of the agricultural sector in the region, limits possibilities to leach salt from soils, increases the risk that fields are fallow with a long-term adverse impact on soils and environment (desertification), fosters over-exploitation of groundwater and decreases groundwater recharge resulting in a sharp rise of salinity in groundwater.

8.2.4 Legal Water Rights and Customary Water Distribution

Water right holders in the Zayandeh Rud basin are urban users, industry, agriculture and the environment. In Roodasht, however, agriculture and the environment within the Gavkhuni wetland are the two major water users. In the Zayandeh Rud basin, traditional distribution of water is based on the Sheikh Bahaei Tomar share scroll, which goes back to the Safavid Dynasty (1571–1629) and includes time and location of water distribution (Mehryar 1999). The scroll is based on a crop calendar and share of available water, with two periods of water supply, for agricultural purposes during 165 days (June 3rd until November 15th), and free water withdrawal and water for the environment during 200 days (November 15th until June 3rd).

According to Sheikh Bahaei, the Zayandeh Rud River basin has 33 major shares, and for each major share, 5-day extraction right of the natural stream flow of the Zayandeh Rud River was determined. The major shares split into sub-regions with regard to local and regional specifics, the number of villages, traditional networks, ownership of lands and vast farming areas. The share scroll entitles Roodasht to six major shares of natural river flow, equivalent to a total of 30 days of water extraction roughly between June 3rd and June 17th, as well as October 30th and November 15th.

The increased water demand of the past years has pushed the government to increase control over water resources by constructing the Zayandeh Rud dam, interbasin water transfers and improvement of water infrastructures. All these developments have changed the natural regime of the Zayandeh Rud River in terms of volumetric as well as temporal water availability. Consequently, the historic Sheikh Bahaei share scroll has been superimposed by a range of political acts.

With the enactment of the Iran Water Law and The Manner of Water Nationalization in 1968, all water resources were declared as public property that the government may distribute according to public interests. Therefore, the responsibility of maintaining infrastructure and supervision of water exploitation was entrusted to the government. This was the legal basis for the Water Equitably Distribution Law adopted in 1983 which formalized customary water entitlements as water rights, by (Article 18—Note 1):

> Water right means the right of use of that water which has been specified and registered in records or ownership documents or orders of courts or other legal documents in the favor of the owners before the date of approval of this law.

As an effect, farmers have been able to prove their water rights (HAGHABE) in the Zayandeh Rud River basin according to records or ownership documents that are ascribed to the historic Sheikh Bahaei share scroll on the one hand and orders of courts or legal documents that are non-ascribed to the share scroll on the other hand.

The priority of the HAGHABE water right was underlined later by the 13th meeting of the Supreme Council of Water that declared that the natural stream flow of river and first Kuhrang Tunnel belongs to water right holders (HAGHABE) and environmental water requirement of the Zayandeh Rud River and the Gavkhuni wetland. Furthermore, allocation of available water resources in dry years shall be decreased relatively by considering the share of water right holders. The situation is particularly complicated since with the second and third national development plan, the government decided to develop modern irrigation networks in cooperation with the Agricultural Bank (Keshavarzi) with financial commitments from farmers who were rewarded with new water entitlements in the form of water subscriptions (HAGHE ESHTERAKI). What is important is that water subscriptions were documented by contracts between farmers and the Ministry of Energy in the Zayandeh Rud basin with the condition that water is only allocated if enough water is available.

The historical evolution of water entitlement challenges water managers in the basin with two main problems amplified during dry years:

- The transition of water distribution patterns based on the natural stream flow to widely accepted and transparent water distribution patterns respecting control of the stream flow (by dam and inter-basin water transfer) did not succeed.
- Too many water entitlements for different stakeholders have been distributed over the decades, exceeding water availability (at least in dry years).

The result was that an opaque and rather reactionary manner of water distribution was established. Currently the lawful and practiced water entitlements of farmers are unclear to farmers and most relevant experts in Roodasht.

Apparently, water distribution within irrigation networks is a practiced custom, loosely based on the traditional Sheikh Bahaei scroll (even though it is outdated) which seems to be the most accepted rule of water distribution amongst farmers. On a basin scale, however, water distribution seems not to be practised according to water rights anymore, but according to other criteria. In Roodasht, the conflict amongst water right holders (HAGHABE) and Haghe Eshteraki holders is no major factor since the distributed amount of Haghe Eshteraki is relatively low compared to actual water right in the region (approximately 20% of the allocated surface water in Roodasht) and most of the Haghe Eshteraki holders are farmers who also have water rights.

8.2.5 Decision-Making on Water Management

During the past decade with water scarcity, available water resources stored in the Zayandeh Rud dam have not been sufficient to fulfil all formally allocated water rights in the basin. The urban and industrial sector has been prioritized for water allocation by the Supreme Council of Water, leaving only very little water left for farming purposes. Furthermore, the upstream region of the Zayandeh Rud basin received apparently more water than the downstream region which is assumed by experts to have happened due to higher political and economic power and vulnerable orchard agriculture in this region. The environs of the Gavkhuni wetland did not receive any water in water-scarce years.

With the change of the presidency in Iran, but also social unrest amongst farmers and the growing environmental awareness of the people, the political agenda on water distribution of the Supreme Council of Water changed. According to the decisions made in the 13th meeting of the Supreme Council of Water in 2014, the natural water of the Zayandeh Rud River should only be allocated to water right holders and also to environmental water rights of the Gavkhuni wetland and the Zayandeh Rud River. The industrial and urban sectors should not further expand their water usage. Furthermore, in the case of drought and water-scarce conditions, if other sectors need to receive water, they must compensate water right holders.

Although according to the new priorities on water distribution the environment is considered a third-level priority for water supply in this region, negotiations and lobbying of local environmental activists and NGOs finally succeeded in having water transferred to the Gavkhuni wetland in 2015/2016.

Decision-making on water distribution in the Zayandeh Rud basin is mainly made by the following main decision-making bodies on different levels:

- On national level, the Supreme Council of Water is the highest decision-making entity. It is chaired by the President of Iran and includes members on national level from the Ministry of Energy, Ministries of Agriculture, Ministry of Interior, Ministry of Industries and Mines, Department of Environment, Management and Planning Organization, etc. The Supreme Council of Water decides on the structure of water distribution on basin scale to different stakeholders, regions and inter-basin water transfer by setting priorities.
- On basin scale, the Coordinating Council for Integrated Management of Water Resources in the Zayandeh Rud Basin is headed by the Ministry of Energy and was established in 2014. It is supposed to improve the collaboration and

coordination amongst the main stakeholders in different sectors and provinces. All authorities in Chaharmahal va Bakhtiari, Isfahan and Yazd provinces have to obey the decisions on water distribution made by the Coordinating Council for Integrated Management of the Zayandeh Rud Basin.
- On the national and provincial scale, the Iran Water Resources Management Company (an agency of the Ministry of Energy) is responsible for enforcing policies and laws related to water resources. The Isfahan Regional Water Company in Isfahan is the provincial unit of the Iran Water Resources Management Company. The Iran Water Resources Management Company and Isfahan Regional Water Company had made decisions on water distribution on basin and provincial level before establishment of a Coordinating Council in 2014. However, today the Water Resources Management Company and Regional Water Company are responsible for implementing decisions on water distribution that have been made by the Coordinating Council for Integrated Management of the Zayandeh Rud Basin.

Under the water-scarce conditions of the past decade, economic-political criteria have gained importance over formal water rights for water distribution by decision-makers. Those economic-political criteria are, for example, the vulnerability to drought and strategic importance of different sectors (urban water use) and regions (e.g. upstream Zayandeh Rud with industry and many water sensitive orchards) and the political and economic power of stakeholders and regions to influence decision-making.

As a result, only little surface water with a strong seasonal variation and fluctuation over the years was allocated to the Roodasht irrigation network in those water-scarce years. The allocation of irrigation water did not meet the expectations of farmers referring to their formal water rights. The following issues on the current process of decision-making on water distribution were brought forward during interviews with local experts and farmers:

- Formal decision-making on water distribution was centralized with the Iran Water Resources Management on national level and Regional Water Companies on provincial level with very little chance of participation for local farmers.
- Since 2014 the Coordinating Council for Integrated Management of Water Resources in the Zayandeh Rud Basin has been responsible for decision-making, with more opportunities for participation of farmers and other stakeholder groups. Nevertheless, it was found that farmers in Roodasht are not aware of this recent development nor of their opportunities for participation in decision-making.
- From a farmers' perspective, the process of decision-making and criteria for water allocation are not transparent and remain unknown.
- Farmers do not understand nor approve decisions on water allocation.
- Parallel institutions and organizations on local level which may be able or even present themselves as capable of influencing decision-making are confusing for farmers.
- The Farmers' Association is the only formal non-governmental representative of farmers participating in decision-making on provincial and basin levels, though

there is a notion that adequate authorization and legal support are missing for the association. Furthermore, local cooperative companies are not politically active and don't lobby decision-makers.

- Political and economic power and lobbying seem to be crucial in the decision-making process. Both of these aspects are likely weak in Roodasht, making the region inferior in the competition with the upstream region of the Zayandeh Rud or other sectors like industry.

These characteristics of, and farmers' perception of, decision-making on water distribution results in a sense of exclusion and a great uncertainty on future water distribution in the region, as well as growing mistrust and conflicts between farmers and government.

8.3 Land-Use Change and Environmental Degradation in Roodasht

This section presents the interdependency amongst discharged surface water and land-use conditions, surface and groundwater quality, desertification and the environmental degradation in Roodasht, observed in the scope of the vulnerability assessment in Raber et al. (2018).

8.3.1 Dependency of Agricultural Land Use on Surface Water Availability

Figure 8.4 on cultivated areas in Roodasht shows that the total cultivated area is strongly dependent on water availability in the Roodasht irrigation network. In dry years, usually farmers plant more crops than they can irrigate with expected irrigation water quantity. They hope for rain in winter so crops may survive, compensate lack of water with saline groundwater, sell premature crops to livestock keepers or hope for financial compensation for lost crops.

For each year between 2006 and 2015, Fig. 8.4 shows the cultivated areas in Roodasht split into areas planted with various crops and harvested including a percentage of wheat and barley of the total harvested area and areas that were planted but not harvested (black and white column). Furthermore, the figure shows the annual water supply (orange line) to the Roodasht irrigation network with a percentage of volume of annual water supplied in springtime (February–July) (Raber et al. 2017).

The presented figure shows the great dependency of agricultural land use on surface water diversion. In their vulnerability analysis Raber et al. (2017) point out specifically, that:

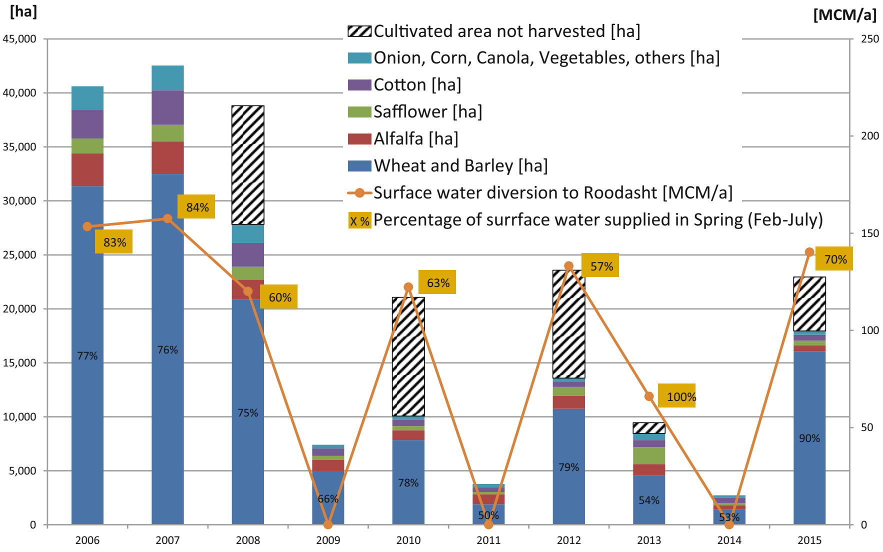

Fig. 8.4 Time series, cultivated areas merged with data on water distribution to Roodasht irrigation network. (Data sources: Isfahan Agricultural Organization and Isfahan Regional Water Company)

- A proportion of cultivated areas could not be sustained and were not harvested in 2008 when surface water supply to the Roodasht irrigation network started to decrease. Another reason may be the decreased proportion of water being supplied during springtime (84% in 2007 and 60% in 2008) which is essential particularly for winter crops wheat and barley (farmers have enough water to plant but not to sustain their crops over the year) (Fig. 8.4).
- In the years 2009, 2011 and 2014, limited cultivation could be sustained, also when no irrigation water was available in the irrigation network. The dataset indicates that these areas were irrigated with groundwater only and were expected to be connected to wells in certain locations taping a productive aquifer that is resilient to limited recharge due to missing surface water in the region (see Fig. 8.5). Nevertheless, also for these areas a decreasing trend over water-scarce years can be observed.
- Product diversity decreased over time, with an increase in the relatively drought- and salt-tolerant grains wheat and barley.
- In the years 2010, 2012 and 2015, the level of cultivated areas decreased by around 40% in comparison to the years 2006–2008, where similar amounts of surface water were available in Roodasht. The reason for this phenomenon is expected to be a strong increase in salinity and declination of (shallow) groundwater resources after a year without recharge of surface water (see Fig. 8.6). This leads to heavy restrictions in application of junctive use of groundwater and surface water for agricultural production and reduces cultivated areas greatly. Furthermore, agricultural areas (lands adjacent to Roodasht) which are not frequently irrigated by surface water are expected to have an increase in soil salinization, making them unproductive for agricultural purposes.

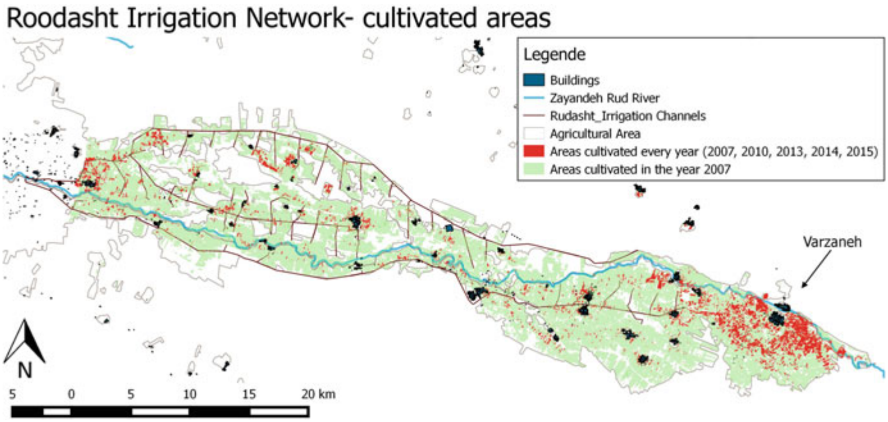

Fig. 8.5 Roodasht irrigation network with area cultivated in 2007 and areas cultivated in 2007, 2010, 2013, 2014 and 2015 detected by remote sensing (data source: Technical University of Berlin, Hengsbach)

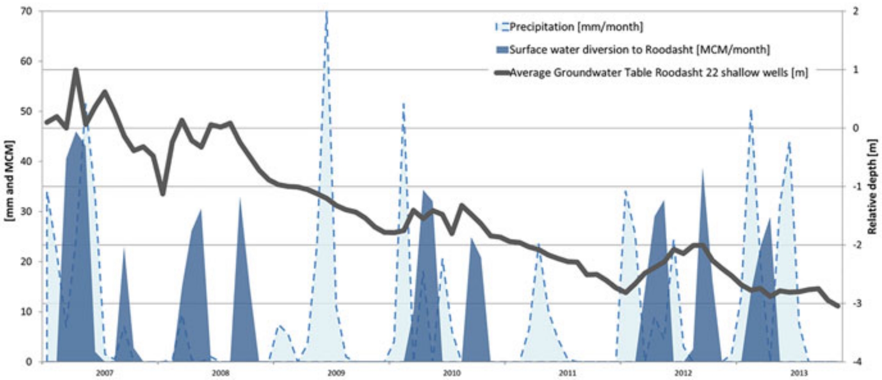

Fig. 8.6 Average relative depth of 22 monitoring wells with a depth of 2 to 15 m in Roodasht with data on water supply and precipitation between 2007 and 2013 (data source: Isfahan Regional Water Company)

In general, sufficient programs or efforts for natural conservation on private lands are not in place in Roodasht. Conservative agriculture, mulch farming, environmental conservation approaches or plantation of live wind breaks around the fields to avoid wind erosion could not be easily found in Roodasht.

In the border areas of Roodasht, on governmental land, few approaches have been made to increase natural vegetation of range lands for erosion and desertification control. Experts discuss the plantation of native consistent plants such as *Haloxylon*, *Calligonum*, *Seidlitzia rosmarinus*, *Nitraria schoberi* and *Artemisia* sp. flanked by rain water harvesting and storage, irrigation of range lands as well as mulching for desertification control of range land (Raber et al. 2018).

The defragmentation of agricultural land is a sub-form of land-use change, supported by the Isfahan Agricultural Organization (with 85% of funding). A large number of farmers in Roodasht own small farms that are fragmented to different plots, which is typical for Iran (Ahmadpour et al. 2013). The uptake of land defragmentation measures is, with few exceptions like Ghurtan Village, generally low in Roodasht, since it requires an intense cooperation and collaboration amongst farmers, establishment of a cooperative company as well as a certain, extensive know-how and investment capacity of farmers' households.

8.3.2 Declination of Water Quality and Land Degradation

The quality of surface water and groundwater depends highly on the availability of fresh surface water in the Roodasht region. When there is not enough discharged surface water, the quality of surface water in the riverbed drops and groundwater salinity increases. This declination of water quality has negative impacts on the soil quality and crop productivity in the region. Therefore, it is worthwhile discussing the relation of the surface and groundwater quality to land degradation and vice versa.

8.3.2.1 Groundwater Quality

The major impact of declining groundwater tables is the growing salinity of groundwater resources, which is of the utmost importance for agricultural production. The expert appraisal of the relationship of groundwater tables and salinization with diversion of surface water to Roodasht is supported in the following by monitoring data on groundwater from the Isfahan Regional Water Company. Figure 8.7 presents a time series on the depth of groundwater tables, and Fig. 8.7 presents a time series on groundwater salinity of selected monitoring wells in the Roodasht region.

Figure 8.6 shows a 3 m average decrease of groundwater tables of 22 sample wells with a depth of 2–15 m within 7 years between 2006 and 2013. In general, the monitoring data from monthly measurements show fluctuations of the groundwater table. During the period with no surface water supply to Roodasht from the end of 2008 until Spring 2010, one can observe a drop (>1 m) of all groundwater tables. During this period (in summer 2009) an intense precipitation event of 70 mm in 1 month was recorded in Varzaneh. No effect of this event is visible in the average of presented shallow groundwater tables. In general, the effect of precipitation on groundwater tables is not observable in this figure because of the low amount of precipitation in Roodasht.

When surface water started to be diverted to Roodasht again in 2010, one can observe a gradual rise in groundwater tables, followed by a drop of the tables in the next water-scarce period until the beginning of 2012 where water tables start to raise

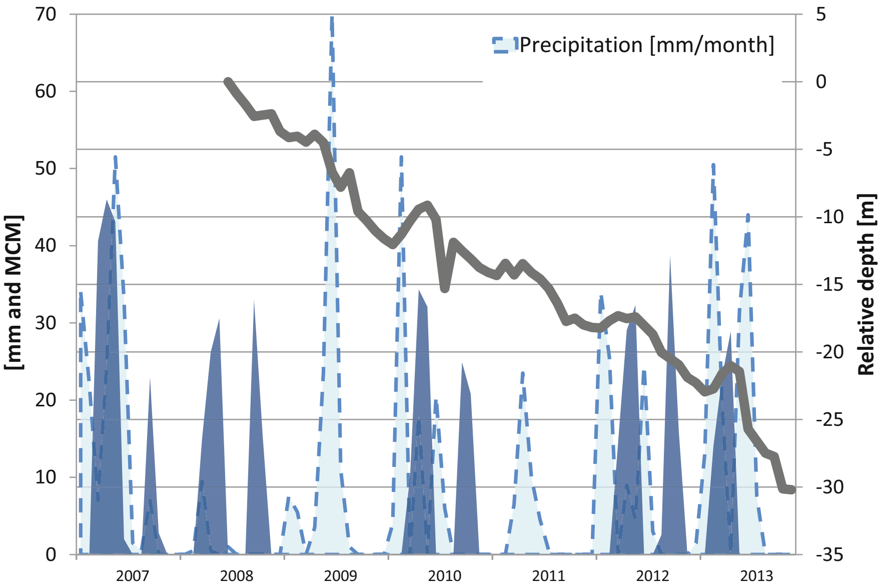

Fig. 8.7 Average relative depth of five monitoring wells with a depth of 25–50 m in Roodasht with data on water supply and precipitation between 2007 and 2013 (data source: Isfahan Regional Water Company)

again analogue to supplied surface water. In general, the dependency of shallow groundwater tables on supplied surface water to Roodasht is obvious in the figure.

Data by the same source on 5 deep wells (initially 25–50 m) show in the period between 2008 and 2013 an immense drop of 30 m, which indicates heavy overpumping of the few sources of deep groundwater in the region (Fig. 8.7). The above-described dynamic of increased water table drops during water-scarce periods is also indicated in Fig. 8.7, but may primarily originate from intensified extraction of groundwater with low salinity during that time.

Figure 8.8 shows a strong fluctuation of groundwater salinity of the four presented monitoring wells during the period between 2007 and 2013. The interpretation of the monitoring data on salinity is challenging due to the long measuring intervals of several months. No clear trend over the whole period may be observed. Anyhow, analogue to the drop of groundwater depths during times with no water supply discussed above, the salinity of monitored well water also increases during water-scarce periods with no surface water diversion to Roodasht and gradually decreases when surface water is being supplied to the region.

Besides these trends the presented levels of salinity are comparably very high for groundwater. In comparison, sea water has a salinity (EC) of approx. 50 dS/m and inhibition of plant growth (yield) starts for the relatively salt-tolerant crops wheat and barley at irrigation water salinity of 6 dS/m (wheat) and 8 dS/m (barley) (FAO 1992).

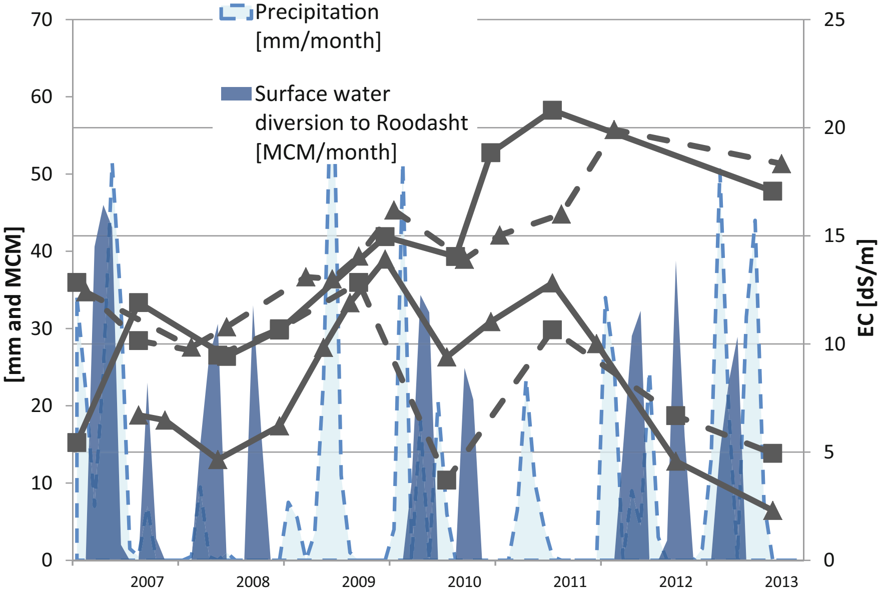

Fig. 8.8 Salinity of groundwater from selected wells in the upstream and downstream part of Roodasht with data on water supply and precipitation (data source: Isfahan Regional Water Company)

Overall the presented data on groundwater support the hypothesis of experts and farmers that surface water supply to Roodasht is vital for a sustainable long-term use of groundwater resources in the region.

8.3.2.2 Surface Water Quality

In interviews, farmers claimed to be satisfied with the quality of surface water, but Droogers et al. (2000) report irrigation water salinity of 2–6 dS m^{-1} in the downstream region of the Zayandeh Rud (confirmed also by Salemi et al. 2000). In their work a simulation model on the impact of water and salt abundance on crop growth in Roodasht was applied. They report for the example of cotton that if water quality improves to 2 dS m^{-1} or even 1 dS m^{-1}, yields may increase to 73% and 77%, respectively, from the status quo with the same volume of annual irrigation applied (Droogers et al. 2000).

Experts state that the river water quality in the downstream region of the Zayandeh Rud has decreased analogue to urban, industrial and agricultural activities in the basin, threatening the ecosystem and water users in Roodasht. In order to evaluate water quality in the Zayandeh Rud River in Roodasht, an Iranian Water Quality Index (IRWQIsc) computed from 11 water quality factors including COD, BOD, Oxygen, EC, total Coliforms, Nutrients (N&P), pH, Hardness and Turbidity

Table 8.1 Classified water quality for different years along the Zayandeh Rud River according to the IRWQIsc

	Abshar region		Roodasht region		
Year	Pole Choom	Pole Ziar	Pole Eghie	Pole Oshkohran	Pole Varzaneh
2010	Rather bad	Rather bad	Bad	Bad	Bad
2011	Rather bad	Rather bad	Rather bad	Rather bad	Bad
2014	Bad	Bad	Bad	Bad	Bad
2015	Bad	Bad	Bad	Bad	Very bad

Source: Data from Isfahan Department of Environment

was applied by the Isfahan Department of Environment. Table 8.1 presents the classification of water quality according to the IRWQIsc in different years on five stations along the Zayandeh Rud River. It can be seen that the water quality is in general rather poor and dropped further over time and along the flow path of the river. It is expected that reasons for deterioration of water quality are discharge of agricultural drainage water and domestic as well as industrial wastewater. Environmental experts state that next to chemically heavily polluted runoff from industrial parks, drainage water from agriculture is heavily polluted due to over-usage of chemical fertilizers and agriculture herbicides and pesticides.

8.3.3 Environmental and Ecosystem Change

The environment around the Roodasht irrigation network is dominated by desert and poorly vegetated range lands. This environment makes the Roodasht area particularly prone to negative impacts of strong desert winds of up to 16 m/s. Environmental degradation through desertification is an ongoing process in Roodasht. Loss of natural ground cover, fallow agricultural lands and salinization of soils are drivers of further desertification and loss of arable land.

Furthermore, the Gavkhuni wetland is drying out with a reported negative impact on the local microclimate, which again increases the risk of hazardous dust storms. The severe outcomes of this land degradation process can be observed particularly in the border areas to the desert in the downstream of Roodasht (Fig. 8.9 presents degraded and abandoned former farmlands in Roodasht). Large agricultural areas have been abandoned due to dropping soil and water quality in the past decade. Next to agricultural fields, the degradation of rangelands is also observed.

To sum up, environmental change in the region is characterized by an ongoing desertification with rapid land degradation, triggered mainly by erosion and deterioration of soil quality as well as the above-discussed poor and unstable water access. During this study no substantial efforts for conservation measures in the region could be identified, neither in agricultural practice (like permanent crop cover, mulching or low tillage) nor in management of rangelands in terms of desertification control (e.g. wind brakes). On the contrary the transformation of natural areas into urban or

Fig. 8.9 Abandoned agricultural fields in the border area to the desert southeast of the village of Varzaneh in Roodasht (Photo: Raber 2017)

agricultural areas, uncontrolled livestock grazing as well as mines further degrade the quality of remnant range land patches (Bateni et al. 2012).

8.3.3.1 Soil Quality

Soil in the region has a high clay content which is affiliated to risks like salinization and erosion, particularly when dried out or fallow. Low organic carbon content, salinization and alkalinity of soils are a risk for agricultural productivity. Soils are getting saline (up to 14 ds m^{-1}) as well as alkaline and are losing productivity in Roodasht. High alkalinity (sodium ion content) leads to erodibility in terms of dispersion of topsoil which decreases porosity and fertility. As introduced before, surface water supplied to Roodasht can have high salt concentrations (up to 6 ds m^{-1}) (Salemi et al. 2000), and groundwater is reported to have even higher salt concentration (up to 25 dS m^{-1}). Irrigation with saline water, coupled with high evapotranspiration and further additions of mineral fertilizers, combined with a lack of rain or surplus irrigation for leaching salts from the soil, fosters salinization. Experts state that next to the above-mentioned sources, salt content in the soil may originate from geological conditions of the alluvial plains of the Zayandeh Rud River as well as capillary rise from shallow and saline groundwater.

In general, besides little organic carbon and high salt concentrations, the soil quality in the Roodasht region has a high agricultural potential due to its clay content. But, high clay fractions in agricultural soils are affiliated to risks like salinization and sodic soils with soil dispersion, clay platelet and aggregate swelling (poor soil structure) and at high risk of water and wind erosion when the soil is dry. The observed wind erosion leads to a loss of the fertile topsoil layer and has a negative effect on agricultural productivity. Wind erosion of the fine textured clay soils also leads to the environmental hazard of dust storms with micro dust. These processes affect the land resources particularly in the border areas to the desert.

8.3.3.2 Gavkhuni Wetland

Under water-scarce conditions, the Gavkhuni wetland and the natural Zayandeh Rud River have been suffering under the competition of different water users for the scarce resource. At the headwork of the Roodasht Irrigation Network, the river course has been entirely blocked for the past years of limited freshwater availability and the water used entirely for irrigation purposes. However, further downstream there is again some water flowing in the river course down to the Gavkhuni wetland. This water is usually drainage or wastewater, which is extremely saline, with EC values as high as 30 dS/m during periods of low flow (Salemi et al. 2000). The decrease in quantity and quality of water flowing into the Gavkhuni wetland has resulted in undesirable ecological effects on the wetland. These conditions have changed the hydrologic regime of the area, so that this natural ecosystem has turned into a salt pan during water-scarce years. The government has recently made rules and regulations on water allocation in terms of an environmental water right. However, water supply to the Gavkhuni wetland is strongly dependent on the political agenda of decision-making on water allocation and relative fulfilment of farmers' water rights in downstream of the basin.

The natural function of the wetland by the complex interactions of soils, water, plants and animals, particularly for stabilizing the shoreline and erosion control, groundwater recharge and purification as well as stabilization of the local microclimate conditions in terms of rainfall and temperature have been diminished over the past years (NWCSAP 2011). Wind erosion and dust storms in Roodasht are currently being discussed amongst experts as a serious hazard for environment, agriculture and people. Due to the drying out of the Gavkhuni wetland over the last several years, experts believe that wind carries away micro dusts from fine silt deposits of the formerly wet area. These silts may contain dangerous heavy metals or other toxic materials originating from polluted water that evaporated or infiltrated the wetland over decades (Raber et al. 2018; Aghasi et al. 2020). The annual dust deposition rate in areas near to the Gavkhuni wetland is about 46 tons/km^2 and micro dust may be carried over large distances up to Isfahan (Aghasi et al. 2020). Respiratory and cancerogenic diseases may follow as a direct result of this dangerous phenomenon. Interviews with experts and researchers on health issues indicated that local people in Roodasht have experienced mental and physical diseases with an upward trend. Unfortunately, during this research, no official data or investigation in this regard could be found.

8.4 Conclusion

In the Zayandeh Rud catchment area, an increase in water users and water extraction, water transfers, climate variability and depletion of groundwater resources have resulted in extreme water shortages and ongoing desertification, particularly in the arid downstream area of the basin. The trend of basin wide water scarcity could be underpinned by data showing a drop of over 40% of water stock in the central Zayandeh Rud dam between the years 2007 and 2015.

Historically, the Roodasht region received water from the central dam twice a year, but in some of the past years, Roodasht did not receive any or received significant amount of water. Compared to other regions in the Zayandeh Rud basin, the cuts in water supply to Roodasht have been higher. The reasons for this imbalance are little political and economic powerplays within the Roodasht region and can also be attributed to the lack of participation of farmers and environmental representatives in decision-making. The lack of irrigation water supply threatens agricultural production and livelihoods of local farmers. The pressure on farmers is intensified by a historically grown complexity of different layers of water entitlements and opaque decision-making on water distribution in the basin which make farmers in Roodasht feel illegitimately deprived of their water rights. As a result the population of Roodasht have a perception of exclusion and corruption causing social conflicts, with protests and fading trust in governmental institutions (Raber et al. 2017).

The reduced supply of surface water impacts directly not only on farming activities but also on groundwater resources, general land-use conditions and environmental degradation in Roodasht. The chapter presents the importance of surface water supply for sustaining local groundwater resources in quality and quantity, which is an important pillar for agricultural production. Therefore, the fate of local groundwater resources is directly dependent on surface water delivered to the region and the type of installed water infrastructure in terms of the use of traditional earth irrigation channels and irrigation methods.

A high risk of desertification is founded in drought-induced soil erosion and salinization, degradation of arable lands and loss of soil cover, little desertification control and environmental conservation. The drying out of Gavkhuni wetland with its central function of stabilizing the local microclimate could also be identified as a direct outcome of short-sighted competition for scarce water resources. These factors are expected to have severe impacts on agricultural activities and human settlements in the whole region. Long-term effects on the Isfahan metropolitan region, with increasing sand and dust storms, carrying polluted micro dust from the wetlands' sediments and changing microclimate are expected by experts. It was found that irrigated agriculture is a powerful measure to prevent the expansion of the desert.

In conclusion, agriculture and the environment in Roodasht are tightly nested and strongly dependent on each other and the access to surface water from the Zayandeh Rud River. The environmental water rights of the Gavkhuni wetland and the Zayandeh Rud River cannot be easily supplied without equitable fulfilment of the agricultural water rights in the entire basin. It can be concluded that the growing social conflict, socio-economic issues and environmental degradation are the consequence of water shortage that have not been well-managed during the last decades (Raber et al. 2018). Without allocation of minimum essential surface water resources to Roodasht and a firm transformation strategy for the region, it does not seem realistic to safeguard farmers' livelihoods, support regional entrepreneurship and protect the environment in the long term. Therefore, an inter- and transdisciplinary joint approach has to be established for sustainable and long-term economic and environmental development in Roodasht and the whole metropolitan region of Isfahan under continuously changing climatic conditions and reduced water availability.

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Chapter 9
Structural Evolution of the Zayandeh-Rud River Basin Based on Historical Climate Changes

Norair Toomanian and Hamid Reza Salemi

Contents

9.1 Introduction

Tectonic movements and erosion deposition sequences affect the evolution of landscapes. Climate condition controls the vegetation cover and the rate of erosion and deposition. Climate changes immensely change the nature of geomorphic and hydrologic conditions to form specific landforms in arid regions. Evolutionary sequences of landscapes are responses to changes of climatic, hydrologic, geomorphologic, and pedogenic processes. Consequently, the same tectonic

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activities, hydrologic and geomorphic processes, and climatic changes govern the landscape evolution and soil development (Shabbir et al. 2013). During developing periods of soils, consequences of every kind of effective changes are reflected and recorded in soil matrix, which are presently called paleosols.

Paleosols are soils formed through geological conditions in the past (Ruhe 1956). They may represent excellent stratigraphic markers and provide important information on paleo-environmental conditions. The formation and preservation of paleosols are closely linked to changes in geomorphodynamic conditions (Kehl and Khormali 2018). These changes are often driven by climate change, which is why sediment-soil sequences may provide excellent records of climate change. Such soils contain features that have not formed under present-day climatic conditions, implying that they experienced at least one significant change in climate, and can hence be defined as polygenetic. The time of climate changing period can be deduced if the underneath layers of younger sediments can be traced and if deposition of these sediments can be dated using geochronological methods.

Buried soils also present some paleoclimatic records and reveal the previous climate changes and evolutionary landscape activities. Brooks et al. (1982) studied the alluvial sequences in central western Iran to construct an archaeological survey. Bobek (1963) used the relative relationships of geomorphic units and their sequence of formation to define the Quaternary paleoclimatology. Dugas (1998) used the geomorphic features to define the late Quaternary variation of Malheur Paleo-lake in eastern Oregon. In their studies, the soil layers were used as witnesses of environmental changes and characterizing the Holocene era. On lagoons of the Baltic Sea, Muller and Mathesius (1999) concluded that it is able to derive the paleoecological evidences from their sediments. Catt (1991), reviewing the soil features as evidences of past records, concluded that both buried and relict soils have great potentiality for Quaternary paleoclimatic interpretations.

Paleosols can provide much more information concerning the evolution of landscapes in every region. Each pedologic development, sharp change of soil layers, mineral accumulation and its variations, presence of abnormally accumulated organic matter, and pedogenic-induced colors are evidences of paleoclimatic changes (Catt 1991; Gerrard 1981). The proxy records of historical events and climate changes are kept in paleosol layers.

Pedogenic and geomorphic features are considered the principal sources of proxy data for paleoclimatic reconstruction (Bull 1991). Ayubi (2002) confirmed that there are some elevated rolling paleo-soils in Isfahan area, which were developed in the pre-Pleistocene period. As he stated, the erosion and deposition processes during the geologic time, especially in the late Tertiary and early Quaternary, had been the main processes of landscape formation factors in the area. Khademi et al. (1997) concluded that some geomorphic surfaces in Isfahan area were developed during pre-Pleistocene periods.

In the Gavkhuni watershed, sedimentological studies and paleoclimatic evidences prove that the Gavkhuni wetland extended over a much larger area during late Tertiary period (Jaafarian 1986). Environmental aridity increases eastwardly in this watershed, while altitude is declining in that direction. A great amount of gypsum and soluble minerals have redistributed in piedmonts and transferred, via the basin's drainage pathways, from uplands to Segzi playas, to Roodasht region, and finally to the wetland (Toomanian et al. 1999).

The covering soils in the Gavkhuni watershed are characterized now by calcic (increasing westward), gypsic, and salic horizons (increasing eastward). There is less knowledge about the evolutionary processes in the eastern part of basin especially the Roodasht area. Although this area has political, economical, and sociological importance, enough information is not available on its Quaternary geologic and geomorphologic settings.

Studying the relationships between these proxy data (pedogenic and geogenic) and their formative processes helps us to reconstruct the sequence of historical events that formed the structure of the Zayandeh-Rud Basin and confirms its evolutionary pathways. The objective of this study is to use the inherited records of environmental changes to reconstruct the landscape evolutionary sequences in the eastern Zayandeh-Rud Basin (especially in the Roodasht area).

9.2 Materials and Methods

The study area is located in the center of Iran. It is the most active part of the Zayandeh-Rud Valley (including the Roodasht area) with typical landforms (Fig. 9.1). Geologic infrastructure in the area from the external reaches coming into the center of the valley contains four units: (I) Mountains are mostly formed by Cretaceous limestone overlaying Mesozoic shale and sandstone (Geologic Survey of Iran 1976). (II) Quaternary alluvial fans and bahadas having late Pliocene rolling plateaus sparsely scattered on them. (III) Playas, which have formed on previous lagoons or on depressions, off the river terraces. (IV) River terraces have been developed along the river's different pathways.

The geomorphic surfaces and spatial distribution of studied soilscapes were stratified using detail geologic infrastructure (Fig. 9.2), bird's-eye photo, (1/55,000) and Landsat images' interpretations. Precedence or retardation in formation of major landscapes was distinguished from their inherent layer unconformities. Different geomorphic units were differentiated because of different sequences of layers assigned to climatic conditions and geomorphic developments (Fig. 9.3). Geomorphic units are inherently different because of the energy and process by which they are formed.

Delineated boundaries of geomorphic surfaces were field checked by excavating 191 profiles in the study area (Fig. 9.2). The soils were classified based on soil taxonomy (Soil Survey Staff 2014). All the soilscapes within different geomorphic surfaces (Fig. 9.4) and the soils in each unit were genetically described and interpreted. Their layers in all contrasting patches of different geomorphic surfaces were related to paleoclimatic specific changing events. Samples from all soil layers were analyzed for pedogenic differences involving texture, structure, and organic matter, clay, carbonate, sulfate, and salinity accumulations. After assigning the

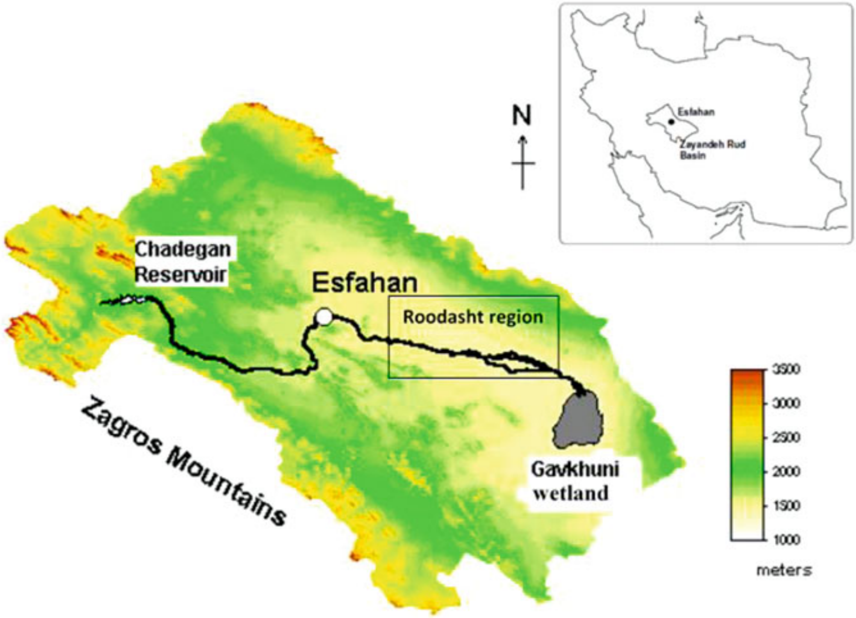

Fig. 9.1 Roodasht area within the Zayandeh-Rud Basin, east Isfahan, Iran

pedogenic evidences to a relative climate and age, these relatively dated geologic and pedogenic features were then used to reconstruct the evolutionary sequence.

9.3 Result and Discussion

Geologic, geomorphic, and pedologic evidences recorded in the eastern area show that the Zayandeh-Rud Valley has experienced some critical evolutionary steps for its formation. The evolutionary steps are shown in Fig. 9.5. The inherited proxy records of past environmental changes are used to reconstruct the past evolutionary history during the late Tertiary and Quaternary. The evidences of these events are presented in Table 9.1. Bird's-eye photo interpretations have distinguished 7 landscapes and 46 geomorphic surfaces in the study area (Table 9.2), which are structured by these sequentially environmental changes over the last 20 million years. Each geomorphic surface has formed through a geomorphic process in a unique geologic time span. Major environmental changes were recorded in soil profiles of Pi (piedmonts), Ap (alluvial plains), Fp (fluid plains), and all Pl (playas) geomorphic surfaces, and Pi 441, Pi 442, Pi 443, Ap 111, and Ap 112 contain records of climatic changes. In the Roodasht area, the Zayandeh-Rud River has changed its route thrice due to consecutive climatic changes that have occurred in its lifetime. This is

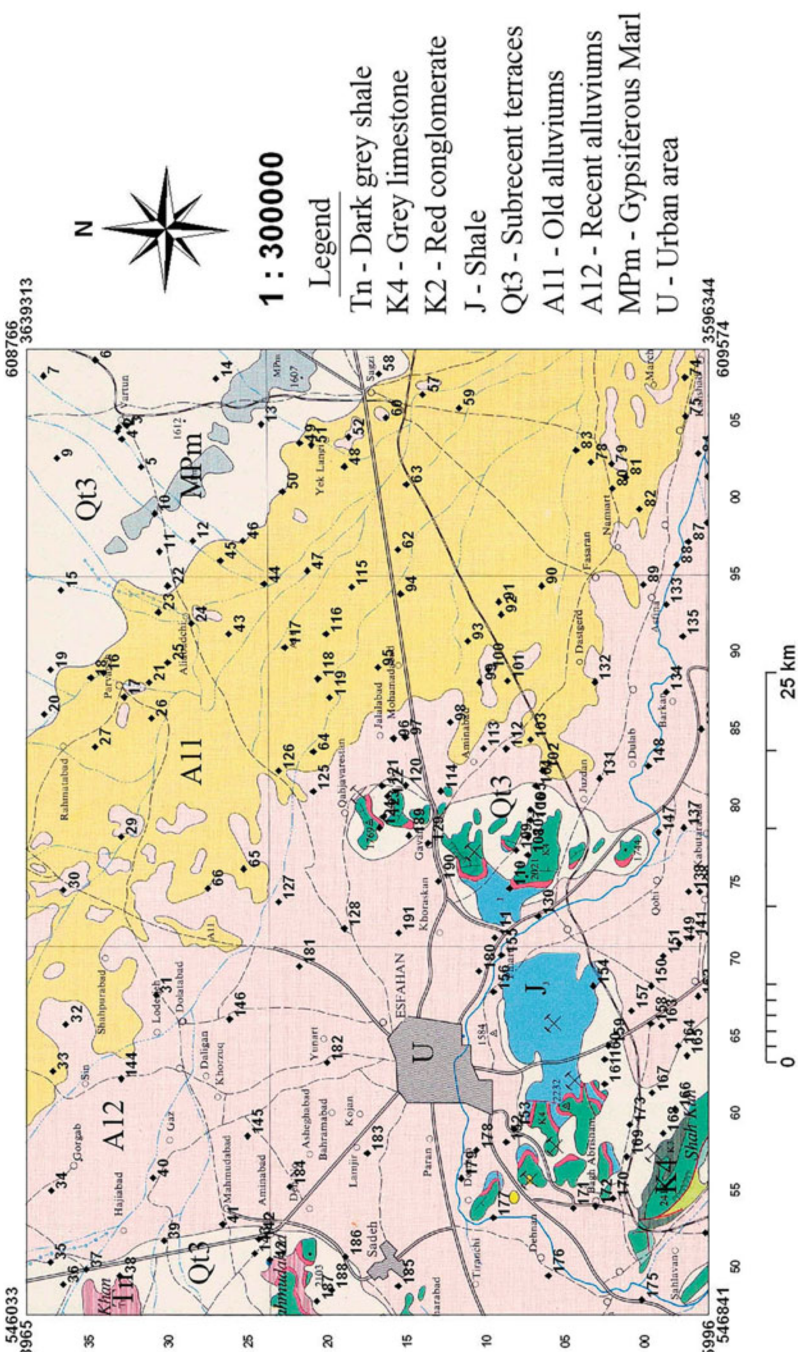

Fig. 9.2 Observation points on geologic map of study area

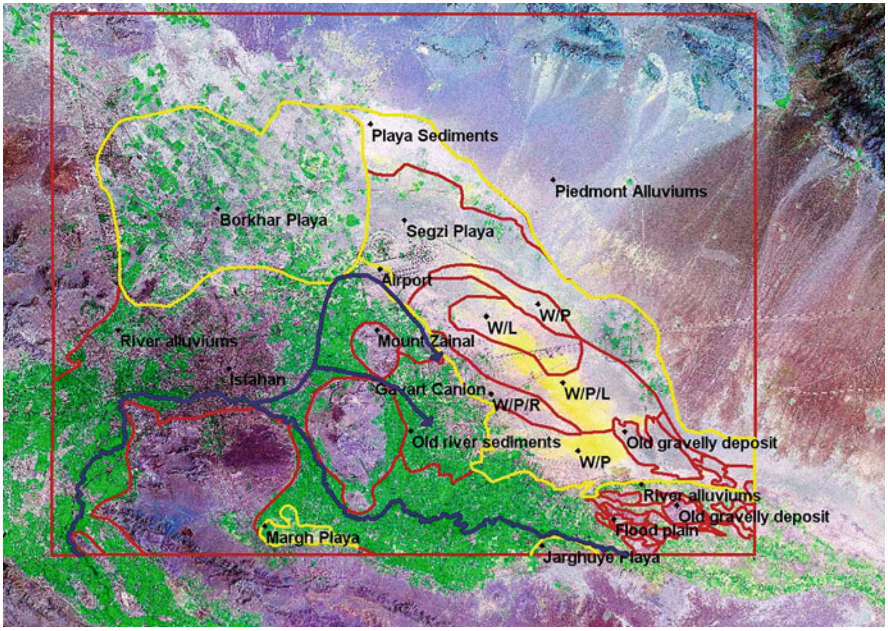

Fig. 9.3 Geomorphic units are (W/P) formed by sequence of wind over playa deposits, (W/L) formed by sequence of wind over lagoon deposits, (W/P/L) formed by sequence of wind over playa and lagoon deposits, (W/P/R) formed by sequence of wind over playa and river deposits, and (W/L) formed by sequence of wind over lagoon deposits

understood from distribution and inherited pedogenic characteristics depicted in soils of different geomorphic surfaces (Fig. 9.4). The steps of landscape evolution in the Zayandeh-Rud Valley are described by order of events.

9.3.1 Zayandeh-Rud River Formation

The southwestern mountains of the valley are part of the relatively young Zagros range, and the northeastern mountains are part of older Karkas range. These ranges have different structural compositions and histories of formation. The presence of the Barremian and Aptian limestone, calcareous shale, and marls, overlying different folded beds of Jurassic and Triassic shale in the Karkas range, indicates a return to marine conditions in the Cretaceous period. The lower Cretaceous sea regressed from the main part of study area in Albian times, before the deposition of the Upper Cretaceous rocks of this mountain (Geologic survey of Iran 1976). The sea regressed eastward but apparently persisted into the Upper Cretaceous and deposited the pelagic sediments until the end of the Cretaceous period. During the end of the

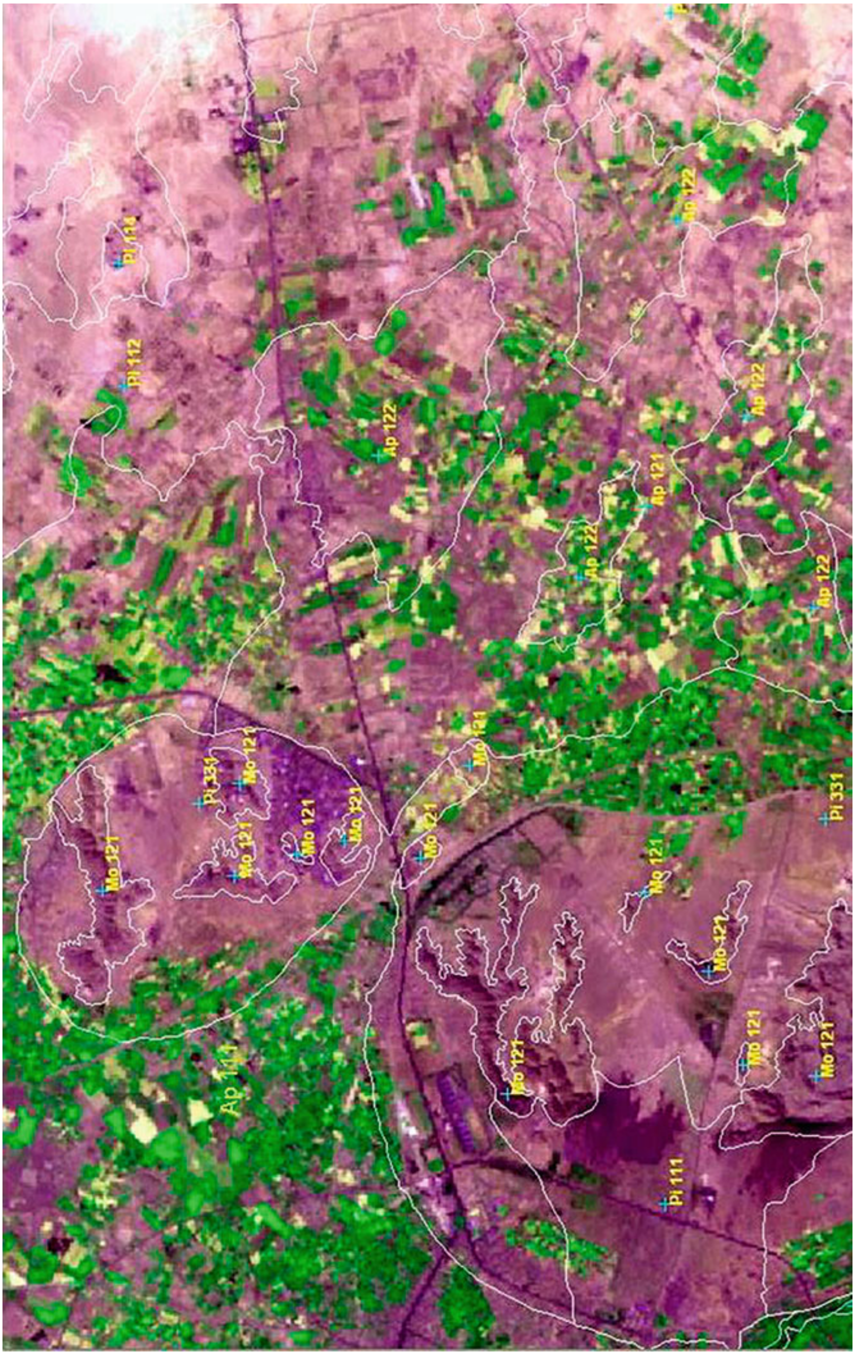

Fig. 9.4 Delineated geomorphic surfaces in the study area, involving Roodasht region (rectangle)

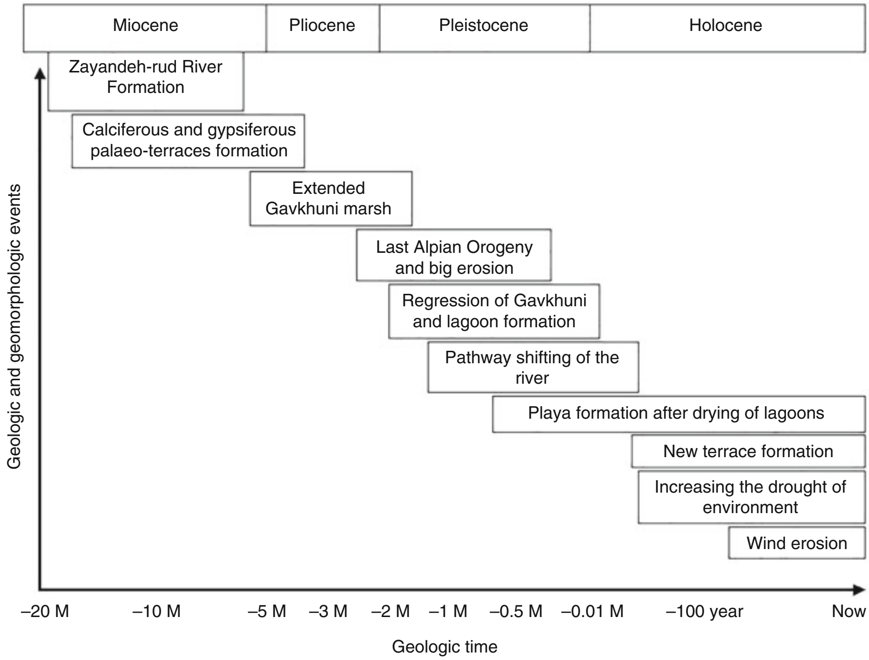

Fig. 9.5 Geologic, hydrologic, and geomorphic sequential events forming the Zayandeh-Rud Valley during late Tertiary and Quaternary

Cretaceous and beginning of the Eocene, the area underwent the Laramian orogeny phase characterized by folding, emergence, and erosive conditions.

The Iranian plate is the result of the collision of the Arabian and Eurasian plates, and the Zagros Mountain is a direct result of this active subduction. Further indicating unstable conditions during the most part of Iranian geologic history, the Lutetian Sea retreated during the Upper Eocene times, and the region underwent folding, uplifting, and erosive activities during the Alpian orogeny movements in the Oligocene period (Darvishzadeh 1992). The Zagros range started to uplift (formation starting) under the active Alpian orogeny process. The Oligo-Miocene Sea, which subsequently invaded the region, deposited some foraminiferal limestone (Qom formation) in the eastern part of the study area. In Mio-Pliocene times, the sea regressed eastward leaving many intermountain lakes in central Iran. In the early Miocene (about 18 million years ago), along with Atikan orogeny (Jaafarian 1986) and an uplifting of the continental plateau, the Zagros range uplifted, and the Gavkhuni depression moved further down by breaking from its eastern parts along the Urumieh-Dokhtar fault. Therefore, the slope gradient from the young Zagros range toward the lower intermountain lake was generated. Consequently, water originated to flow from elevations of the Zagros range toward the Gavkhuni wetland, which was left by the regressing Mio-Pliocene Sea (Jaafarian 1986). By down

Table 9.1 The historical events with their relative evidences

Geologic and geomorphic events	Activation period	Climatic, geologic, geomorphic, and soil evidences
Zayandeh-Rud formation	Early to late Miocene	Uplifting of Zagros range with Alpian orogeny, sinking of Gavkhuni area, and breaking from its eastern formations
Paleo-terrace formation	Early Miocene to early Pliocene	High slope gradient formation by previous act, sinking of Gavkhuni area for second time, scattered elevated thick and coarse gravelly geomorphic units in piedmonts, playas, and river alluviums. Extensive secondary calcium carbonate and gypsum accumulated in polygenic soil profiles of MPm, Qt1, and Qt2 formations. Gravelly layers underlie the piedmont, playa, and terrace depositions
Extended Gavkhuni	Late Miocene to early Pleistocene	Black layer in deep excavations near Isfahan city (4–8 m deep) which is supposed to be the remainder of extended lakes meadow. Specific shallow marine palynomorphs detected in buried soils of Rangi Deh area (east of study area). Detected shorelines
Intensive erosion	Late Pliocene to late Pleistocene	Last uplifting of Zagros range and sinking of Gavkhuni area. Uplifted rolling gravelly land units scattered on different landscapes of valley (landforms of Pi 511, Pi 512, and Pi 711)
Lagoon formation	Early to late Pleistocene	Thick dark layer containing organic materials under most of playa sediments in the Segzi and Margh playas. Existing specific wetland fossils in all black layers
River shifting	Early Pleistocene to early Holocene	Very thick pure river alluviums under playa and lagoon depositions (Ap 122). River meanders detected by bird's-eye photo interpretation (Ap121). Mines of civil raw material along river's different pathways
Playa formation	Mid-Pleistocene to present	Fine sedimentation in four depressions of valley with playa geomorphic surfaces
New terrace formation	Early Holocene to present	Three different terraces lay along new pathway of river (Ap 111, Ap 112, Fp 111, Fp 112, Fp 211)
Wind erosion	Last century	Active wind erosion in the Segzi playa.

cutting the riverbed in the steep parts, it laid the eroded materials in the eastern flat parts, forming its river terraces.

9.3.2 Paleo-terraces Formation

In the early Miocene, steep slopes and high hydraulic gradients, resulting from the uplifting of the Zagros range and the subsiding of Gavkhuni wetland, provided a great amount of driving force for an erosive mechanism. As a result, an immense

Table 9.2 The legend of hierarchical geomorphologic land units distinguished in study area

Units	Landscape	Landform	Lithology	Geomorphic surfaces	Code
1	Mountain	Dissected ridge	Marl limestones (K4, K2) and dark gray shale with limestone	Structured surface	Mo 111
2	Mountain		Marl limestones (K4, K2)	Structured surface	Mo 121
3	Mountain	Rock pediment	Eroded calcareous and dark gray shale with limestone	Scarp slope	Mo 211
4	Hill land	Dissected ridge	Basal conglomerate (OMC)	Slope facet complex	Hi 111
5		Eroded ridge	Dissected dark gray shale with limestone (Tn), gypsiferous	Structured surface with braded stream network	Hi 211
6		Rocky high hill	Remnant of shales (J)	Slope facet complex	Hi 311
7	Piedmont	Pediment	Remnant of shales (J)	Slope facet complex	Pi 111
8		Flash flood delta	Quaternary alluvium	Outwash sediment with divergent drainage network	Pi 211
9				Outwash sediment (coarser)	Pi 212
10		Alluvial fan	Alluvium of foraminiferal limestone and basal conglomerate	Apical part	Pi 311
11			Alluvium of dark gray shale with limestone (Tn, naiband formation)	Apical part, slope facet complex	Pi 321
12			Alluvium of marl lime-stones (K2, K4, etc.)	Slope facet complex	Pi 331
13				Slope facet com-plex, cultivated	Pi 332
14			Alluvium of marl lime-stones (K2, K4, K7, etc.)	Active fan	Pi 341
15		Bahada	Alluvium of foraminiferal limestone, basal conglom-erate, and volcanic	Middle part	Pi 411
16			Alluvium of Andesite, granodiorite, and foraminif-eral limestone	Apical part	Pi 421
17				Apical part (extremely braded drainage)	Pi 422
18			Alluvium of foraminiferal limestone (OM)	Apical part, with dens drainage network	Pi 431
19				Middle part	Pi 432

(continued)

Table 9.2 (continued)

Units	Landscape	Landform	Lithology	Geomorphic surfaces	Code
20				Distal part, with dens drainage network	Pi 433
21				Distal part with dens drainage network, finer	Pi 434
22				Distal part calcareous	Pi 435
23				Distal part, salt crusted, gypsiferous	Pi 436
24			Alluvium of marl lime-stones and dark gray shale (K4, K2, Tn)	Middle part with parallel drainage pattern	Pi 441
25				Middle part with less drainage	Pi 442
26				Distal part with dens drainage network	Pi 443
27		Dissected old bahada	Alluvium of foraminiferal limestone (OM)	Paleo-terrace, undu-lating plateau	Pi 511
28				Paleo-terrace, with braded intense network	Pi 512
29		Old bahada	Fine marl gypsiferous sediments	Paleo-terrace, flat, salty	Pi 611
30			Fine marl alluvium	Paleo-terrace, distal part	Pi 621
31		Rolling old bahada	Coarse gypsiferous alluvium	Paleo-terrace, gyp-sum plateau	Pi 711
32	Alluvial plain	Alluvial flat, river terraces	Zayandeh-Rud River alluviums	Cultivated terraces	Ap 111
33				Cultivated terraces, salty	Ap 112
34			Old river sediments	Meandering com-plex facet	Ap 121
35				Cultivated old river terrace	Ap 122
36	Flood plain	Lowest river terrace	Recent alluviums	Channel margins alluvium, cultivated	Fp 111
37				Channel margins alluvium, culti-vated, salty	Fp 112

(continued)

Table 9.2 (continued)

Units	Landscape	Landform	Lithology	Geomorphic surfaces	Code
38		Seasonal river flood plain	Recent alluviums	Salty gleyed fine alluviums	Fp 211
39	River	River sediments	Recent gravelly alluviums	Channel sediments	Ri 111
40	Playa	Segzi basin	Alluvio-lagoonary fine sediments, extremely salty and gypsiferous	Wet zone, flat, salty, cultivated	Pl 111
41				Wet zone, flat, very salty	Pl 112
42				Soft clay flat, very alkali, with drained groundwater	Pl 113
43				Soft clay flat, gypsiferous, extremely salty	Pl 114
44		Borkhar Basin	Alluvial fine sediments, slightly salty	Soft clay flat, cultivated	Pl 211
45		Margh Basin	Alluvio-lagoonary fine sediments, gypsiferous	Puffy ground, lagoonary, gypsiferous	Pl 311
46		Jarghuye Basin	Alluvial fine sediments, extremely salty and gypsiferous	Soft clay flat, cultivated	Pl 411

amount of calciferous and gypsiferous gravelly material eroded and was unconformably deposited on different older beds of the western and eastern parts of the valley (Ministry of Industry and Mines 1978). These erosion and deposition processes continued until the early Pliocene and brought about the formation of thick gravelly (calciferous or gypsiferous) sediments on piedmonts of the entire valley. The evidences of this thick sedimentation are the elevated rolling older terraces that extended in two sloping sides of the valley off the playa areas (Fig. 9.6). To a great extent, these geologically called “gypsiferous marls (MPm),” “old terrace deposits (Qt1),” and misunderstood “old Zayandeh-Rud River deposits (Qt2)” lie outside the study area in the valley (Ministry of Industry and Mines 1978). Consequently, there are extensive amounts of secondary calcium carbonate and gypsum in soils developed in the western and eastern parts of the valley. The gypsum mineral of these sediments originated mainly from the surrounding mountains in the Jurassic and Cretaceous ages (Toomanian et al. 1999) and the brackish shallow Oligo-Miocene fluctuating Sea (Khademi et al. 1997). These unconsolidated coarse alluviums are formed by rounded gravels and intercalated dense gypsum minerals. The elevation of these geomorphic surfaces and the amount and form of gypsum inside and the completely round gravels, which are different from other local features, induce the

Fig. 9.6 Old terrace depositions related to thick gravelly alluviums

idea that they are not formed in this climatic condition. The size and roundness of gravels show that they formed after long transformation under more humid climatic conditions. The form and compactness of gypsum, infilled between gravelly matrices of these rolling gravelly alluviums, confirm the intensive and chronic translocation of this mineral (Toomanian et al. 1999, 2001). Isotopic study of Khademi et al. (1997) has shown that these gypsums are formed by sedimentation of brackish Tertiary seas and re-translocation after sea regression in the Oligo-Miocene periods. The immense amount of secondary calcium carbonate formation in soil layers in the south-eastern part of the valley confirms the age of these deposits (Noorbakhsh 2002).

9.3.3 Extended Gavkhuni Wetland

During the uplifting of the Iranian central plateau in the Mio-Pliocene, the previous sea regressed eastwardly leaving the vast Gavkhuni wetland behind. The extent of this wetland in the Pliocene period was considerable and occupied a vast eastern area of study (Karimzadeh 2002). This wetland was fed by the Zayandeh-Rud and some torrential flows of the Khoshkeh Rud seasonal river. The organic black colored layer, which is seen in deep excavations of Isfahan city, is good evidence of the Gavkhuni wetland extension. As mentioned in the literature, these blackish materials are remnants of fringe meadow in this wetland. The palynology analysis of Ayubi (2002) in buried soils of Rangi Deh (inside the study area) shows that the palynomorphs of this black layer are of specific shallow marine and are different from those that have been distinguished in the Segzi playa. Ancient shorelines detected in the Zayandeh-Rud Valley confirm this hypothesis (Ramesht 1994). The fluctuation of Paleoclimate in central Iran was concordant with glacial and interglacial periods of northern Europe (Motamed 1988, 1997). Fluvial or more humid periods of the area were simultaneous with glacial and the dry periods with interglacial phases (Ramesht 1994). This fluctuation resulted in developing some polygenetic soils on paleo-terraces and the formation of black layers on the Gavkhuni wetland's different terraces. These black layers in different places are seen a few meters deeper than those observed in Segzi playa and are observed in places further from the playas area.

9.3.4 Intensive Erosion

There are no signs of great changing activity in the area from the early Miocene until the last phase of Alpian orogeny (about 2 million years ago, Darvishzadeh 1992). The most substantial geologic evidences of tectonic activity in the area are the last uplift of Zagros, the folding of travertine, which was laid on Oligo-Miocene limestone (Qom Formation) in Zefre, north of the study area, and the sinking of the eastern part of the valley and the Gavkhuni wetland once again (Jaafarian 1986). The hydraulic gradient formed by these activities caused intensive erosion and sediment transportation thereafter. Via an erosive process, most of those thick gravelly and gypsiferous paleo-terraces from the sloping sides of the eastern part of the valley washed away, but some parts were left behind (Fig. 9.6). The extending directions of these hilly formations are mostly along the slope direction of drainage systems, which shows that they were formed by an erosive process of running water from mountain fronts downward. The presence of those rolling landforms in the Segzi playa and in the river terraces near the bottom of the valley shows that previous old gravelly piedmonts covered all the sloping and flat landforms. These coarse deposits being overlaid by playa and river terrace sediments, in most part, prove that the playas and the terraces are completely newer landforms. This confirms that the previous vast Gavkhuni wetland retreated from this area during the late phase of this erosive period and also shows that these rolling gravelly plateaus are the oldest land formations among unconsolidated landscapes in the study area. These paleo-terraces are characterized by the definition of Pi 511, Pi 512, and Pi 711 geomorphic surfaces in the study area (Table 9.2). It is assumed that these rolling gravelly alluviums are remnants of those thick gravelly old terraces made in the Pliocene. The area shows no evidences of other landform formation from Pliocene to Pleistocene; it means that this erosion process was the major hydrologic process prevailing during that period. Simultaneous with this extensive erosion and after a steady period of warming and drying, the wetland retreated and had changed into some local lagoons by the late Pliocene. These landforms are not subjected to cultivation in the Roodasht area.

9.3.5 Lagoon Formation

Because of wetland retardation, during the previous erosion period, some shallow depressions were left behind. Four depressions are distinguished in the entire valley. The first was Borkhar, located in the north of Isfahan City. This basin was fed by the Khoshkeh Rud seasonal river, which brought the eroded coarse and fine calcareous materials from Jurassic and Liassic shales or Cretaceous marl limestones from the northwest. Because in this depression any sign of lagoonization was detected, we are assured that no lagoonal condition prevailed in this basin. Segzi depression was the second, located in the northeastern part of the valley. After the filling up of the Borkhar depression, the fine eroded materials moved farther to the east and deposited in the Segzi depression. The neighboring gravelly piedmonts and Old Zayandeh-Rud route (route 1) fed this depression. Margh, an abandoned little depression, was the third basin located in the southern part of Isfahan City. Irrespective of its limited area, the lagoonization process had taken place in it. Streams gathered from Kolah Ghazi Mountain, south of the study area, fed this depression. The fourth depression was Jarghuye, which extended outwardly in the southeastern part of the valley. During post Alpian orogeny activities in the late Pleistocene; both Segzi and Margh depressions turned to lagoonal conditions, which persisted up to the Holocene (Figs. 9.7 and 9.8). Observing playa sediments on top of those rolling old alluviums within the Segzi playa, compared with the height of those plateaus within river terraces near the bottom of the valley, proves that the Segzi depression had sunken simultaneously with that extensive erosion process. The strongly black layers of marsh remnants, at different depths, are distinguished in most of these depression surfaces (Ayubi 2002). The lagoonal black sediments are present in substratum of most parts of the Segzi and Margh depressions. Figure 9.8 shows the thickness and the black color of sediments retained in the Segzi playa marsh (fine, mixed, thermic, gypsic haplosalids). The mollusk and snail fossils existing in these sediments are witnesses of good biotic marsh conditions. The extent of lagoon in the Segzi basin is considerably vast (Fig. 9.3). The thickness of black layer decreases, and the depth increases at the border of this lagoon in the Segzi basin. The geomorphic surfaces of the Segzi and Jarguye basins in the Roodasht area are Pl114 and Pl411. These units show different reactions to irrigation programs because of their inherently different characteristics. To extend the irrigation systems on these surfaces, the focus should be kept on the salinity, groundwater level, and depth of lagoonal black layers and its sequence in soil profiles. This geomorphic unit has high water table potentiality, and those black layers, in low depths, prohibit the root growth of any plant. In cultivation of Pl411 unit, high salinity, soil fine texture, drainage, and high water table should be focal points of any cultivation plan.

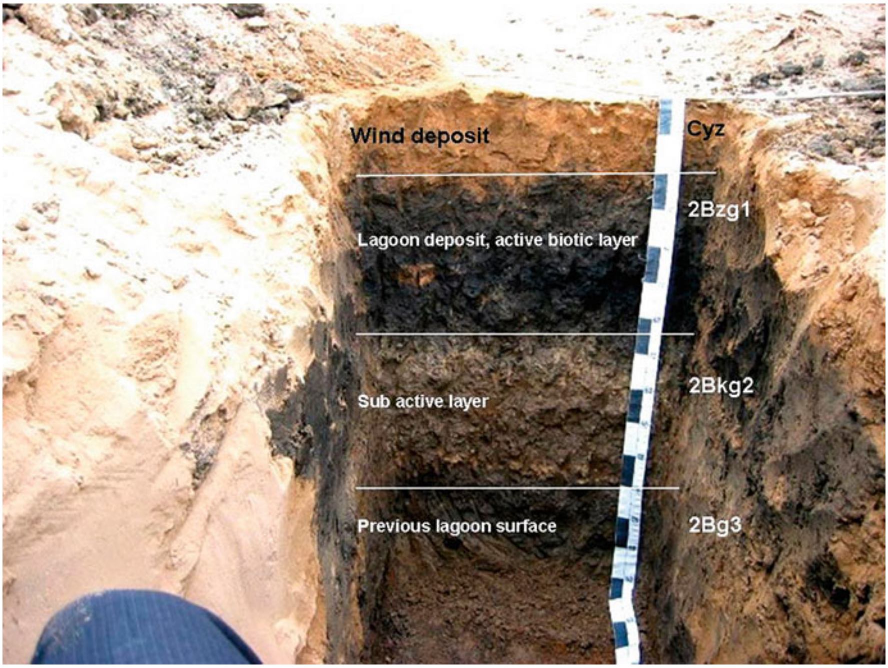

Fig. 9.7 The thick layers of lagoon sedimentation in the Segzi playa

9.3.6 River Route Shifting

After the last phase of Alpian orogeny and following the huge amount of material transportations, the Zayandeh-Rud River tried to reconstruct its terraces around its pathways toward the Gavkhuni wetland in the early Pleistocene. In late Pleistocene periods and simultaneously with lagoon formation periods, the river in the Isfahan area passed from its northern route (Fig. 9.3, route 1), where its upper terraces lay (Ramesht 1992; Ahmadi and Soltani 1996; Jaafarian 1986). In this route, river ran from the place of newly constructed Behshti airport and then turned southeast. Excavations for raw civil materials and the extraction of huge amounts of sand and gravel from deep mines around this route induce only one thing in our minds: that turbulent water had passed through this area for a very long time (Figs. 9.1, 9.2, 9.3, 9.4, 9.5, 9.6, 9.7, 9.8, and 9.9).

Existing thick layers of pure coarse river alluviums under playa sediments and over black layers of lagoon sediments, near the entrance to the Segzi lagoon, show that the river in its northern route had once fed the Segzi lagoon. This also proves that the playa formation process took place much later than the sedimentation of river alluviums. Profiles described on the upper terraces of this route located in the western part of the airport (not affected by wind erosion) show completely improved soil layers (fine-silty, mixed, thermic, typic haploargids). Argillic horizon formation

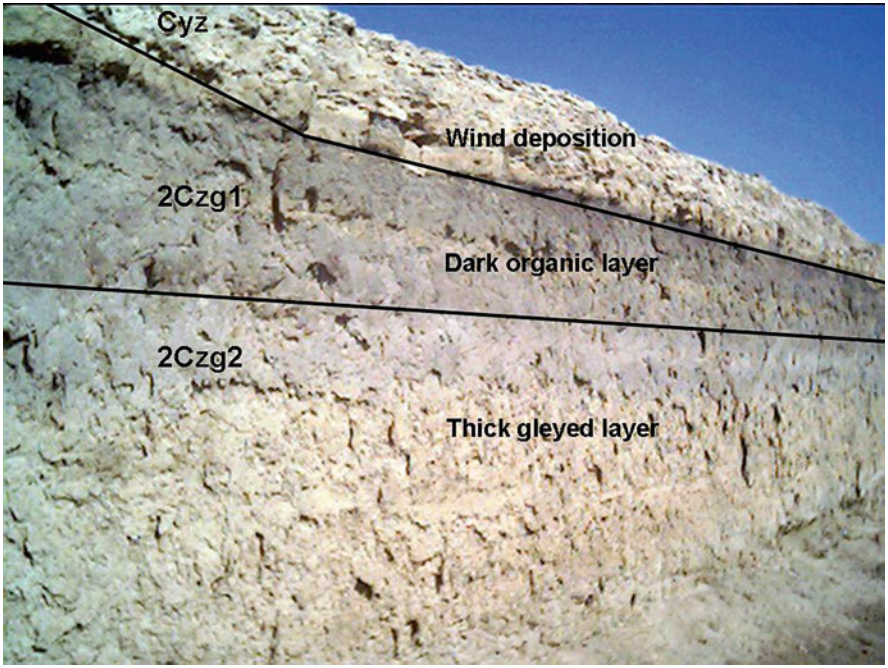

Fig. 9.8 Thick lagoon deposition containing mollusk and snail fossils

in the upper terraces of these soils in the Khorasgan area shows the comparably old age of these sediments. The river turned southward after passing the mountain neck and laid its gravelly terrace in that direction (Ap 122, Figs. 9.3, 9.4, 9.10). Thick layers of rounded gravels under playa sediments, in the north of the Zainal Mountain, also support this hypothesis: that a large amount of water flowed from here during that period. In the mid-Pleistocene, drought increased (Krinsley 1970), and consequently the ability of the water to turn in the Zainal Mountain decreased. Therefore, the river changed its route and opened its way to the east from Gavart canyon (route 2 Fig. 9.3). Trident flow streams of river are clearly distinguished in the interpretation of a bird's-eye photo (Ap121, Fig. 9.10). The undeveloped soils laid by this route between lenses of previous Ap 122 soils are differentiated by bird's-eye photo interpretation. A thin, fine surface layer and gravelly thick substratum are the main characteristics of these soils (Fig. 9.11). Ever-changing soil layers and types are other characteristics of these soils, which resulted from continuous sedimentation of the meandering river in this route. Permanent renovation of these coarse river alluviums prevents their stability and therefore their development. The most eastern part of these old river terraces is covered by playa sediments. It proves that playa formation sped up after river sedimentation, in the early Holocene. Figure 9.9 shows the amount of playa sediments covered in previous river alluviums.

The differences between soils developed on Ap 122 (older, route 1) and Ap 121 (old, route 2) geo-surfaces are the thickness of finer surficial layer which is

Fig. 9.9 Thick river alluviums under playa sedimentation, route 1 of the Zayandeh-Rud River near Beheshti Airport

greater in Ap 122 unit. These soils have suitable classes for arable cultivation if the surficial layer is more than 50 cm and land-use change does not ruin the productive potentiality of the area. Gravel mining in agricultural lands is the worst land-use change which affects the irrigation planning in these productive areas (Figs. 9.9 and 9.11). Water distribution programs should consider the extent of the excavated areas, which have lost their productivity and need supplementary work for increasing the water-holding capacity and soil productivity.

9.3.7 Playa Formation

The eldest depression in the study area is the Borkhar with deep and multi-genetically developed soils (fine-silty, mixed, thermic, typic calciargids). It is supposed that these sediments started to deposit in the early Pleistocene when Segzi playa was in its lagoonal state. The depth of the soil polygenetic layers, in this depression, receives to some 30 m in south margin of this depression (the Shahpur-Jadid area). The depth of infilled layers represents the preliminary depth of this depression. Most of the infilled materials were eroded and translocated materials from different shale or Cretaceous marl limestones. The coarse materials were laid

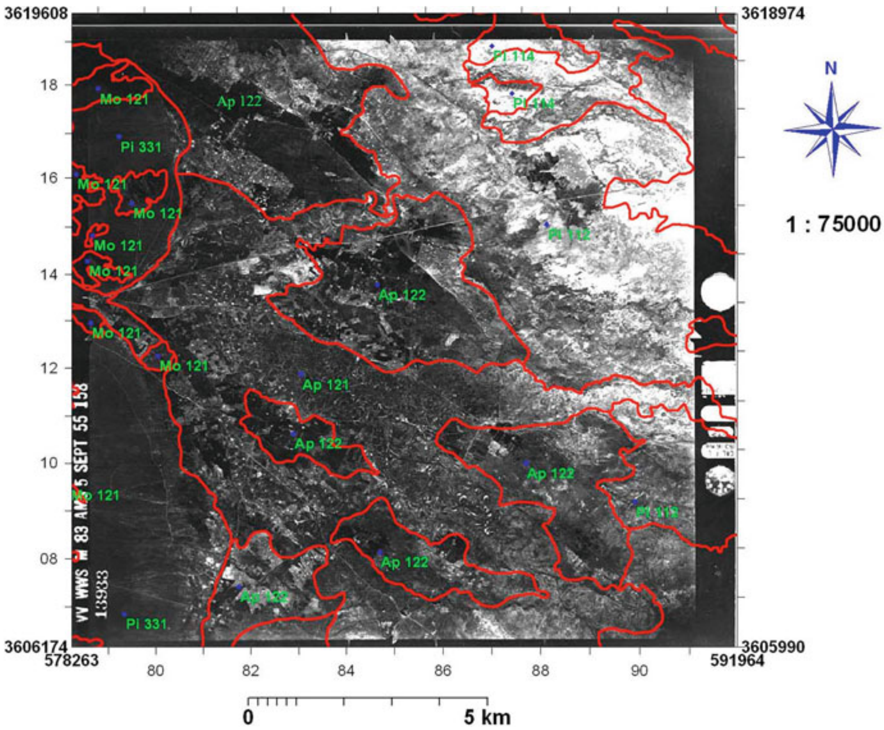

Fig. 9.10 River alluviums in route 1 (older, Ap 122) and route 2 (old, Ap 121)

down at the entrance of the depression (northwest) where the cities Murcheh Khvort and Shahin Shahr are now located and where loose fine material was deposited in the central to eastern part. A thick layer of whitish calcareous fine materials were deposited at the center of the basin (30–40 m deep qanat wells are good witnesses for these sediments). The formation of argillic horizon, secondary carbonate calcium accumulations, and developed structure in Bt horizons of soils in this landform shows its relatively elder age. Pedogenic formation of argillic horizons and the existence of lime dulls sequentially formed in thick layers represent the perpetual filing of this basin over a long time span. The southern border of these sediments is located around Shahpur Jadid and Ashegh Abad cities, where it borders Zayandeh-Rud's upper terrace. On this border, some intercalations have taken place between two kinds of sediments. The presence of relatively developed soils and pedogenic lime dolls (Fig. 9.12) in all depths of these sediments proves the old age of these sediments, presumably deposited in the early Pleistocene. The decreasing thickness of sediments and the northward soil development show the regressive front of the deposition process especially at the entrance of this basin. Because no sign of black layer was distinguished in any layer of this depression, we are assured that no lagoon was formed in the basin. After filling up the Borkhar depression, the fine eroded materials moved farther to the east and deposited in the Segzi depression.

Fig. 9.11 Typical soil layers in Ap 121 geomorphic surface, river alluvium of route 2

Fig. 9.12 Pedogenic lime dolls formed in soils of the Borkhar playa (Pl 211)

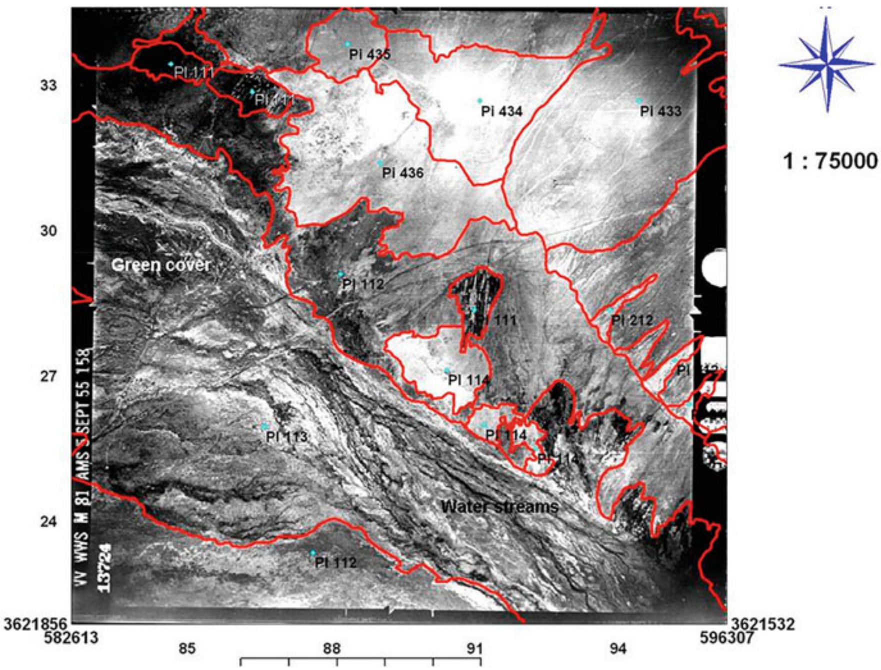

Fig. 9.13 Drainage pattern and green cover condition (black reflectance) in the Segzi playa (Pl 113), early1940

With the intensifying drought in the late quaternary, the river lost its potency to pass the Gavart pathway and changed its way to the existing third route (Fig. 9.3). Accordingly, the Segzi depression was left abandoned with no feed and intensive aridity. Such conditions favor playa formation and extension. Playa formation in depressions resulted in different geomorphic surfaces, which are different by slope, moisture content, and soluble mineral accumulations. They therefore inherited different characteristics.

After the lagoons dried up, playa formation in Segzi and Margh depressions started in the early Holocene (Krinsley 1970). Fine-textured and saline playa sediments overlaid on lagoon layers of Segzi, and Margh playas support this hypothesis. In the Holocene and for a long time, the ecosystem of Segzi playa was in considerably better condition than today. The high water table (waterlogged) and surficial flowing water in drainage network and a good green cover are good evidences of an active environmental condition (Fig. 9.13, early 1940s). In addition, the remnant of dried roots (Fig. 9.14) and meadows are still preserved in the area showing the hydrological and ecological conditions prevailed until recent decades. Figure 9.3 presents the extent of playas formed over the lagoons in the study area. The drain convergences in the far eastern part of Segzi playa formed stable water flows toward river terraces, which developed some waterlogged soils around those drains. The condition and extent of playas are stable for as long as its hydrology and moisture are

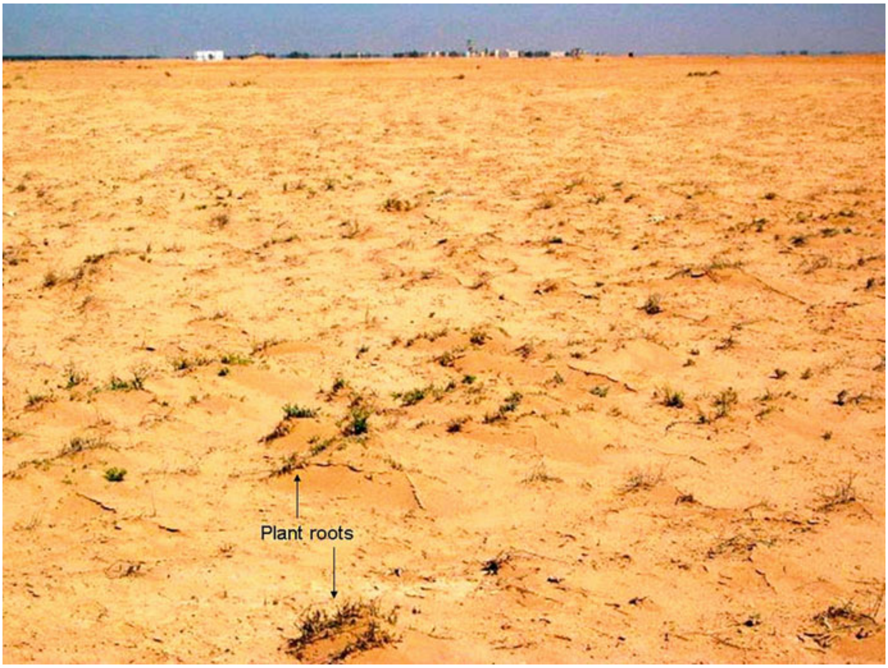

Fig. 9.14 Remaining plant roots after drying up of the Segzi playa (Pl 113)

guaranteed. Otherwise, it changes into an invasive landform. Segzi playa (including the Roodasht area) and the Gavkhuni wetland inherently have such potentiality to change into an invasive region, which can expand its borders to connected agricultural lands and outcast the saline materials to far civilized territories. In this immense drought condition, all the playa geomorphic surfaces would expand outwardly into the Roodasht area and would be salinity generator for far and near agricultural sectors. As such, any irrigation layout, be it irrigation platform or distribution system, should consider the surface extension of playas toward agricultural lands and the extent by which the salinity is being distributed. This layout should measure the amount of risk by accepting such amounts of salinity and decreasing crop production in the Roodasht area. To reduce the inverse interference of playa extension and salinity invasion (by break through process and wind distribution), the comprehensive irrigation layout should consider the feeding amount of water, which should be given to these playa geoforms to stabilize their hydrologic condition.

9.3.8 River's New Terraces Formation

As described, the Holocene period starts concordant with the commencing of the last interglacial phases. Therefore, in central Iran, an intensive drought driving force

Fig. 9.15 Reduced soils in previously waterlogged land units (Fp 211)

originated (Motamed 1997). As mentioned above, due to the decreasing strength of the river's flow in early Holocene period, the river changed its way to route three. Preserving this route until now, tree terraces have been laid around its way to the Gavkhuni wetland. Distinguished geomorphic surfaces in terraces are Ap 111, Ap 112, Fp 111, and Fp 112. The terraces in this new route are laid in different thicknesses and layer sequences. As depicted in Fig. 9.9, the first terrace is tens of meters thick including fine and coarse river alluvial materials laid in different sequences, depending on the duration of each flow and strength of flow at every point. The second terrace is laid like the first one but with a lesser thickness and the third terrace a light textured strip of sediments near the river (Fp 111) or fine-textured alluviums around the seasonal or temporary flooding watercourses gathered from drain convergences of Segzi playa (Fp 112). The second form of third terrace is developed under waterlogged conditions because the soils around those drains had always been saturated in previous times. The studied soil profiles show that the upper terrace is distinguished by its developed argillic horizon and the middle terrace is characterized by its cambic horizon and the rest of the soils without any development belong to lower terrace of this river. The reductive condition of those waterlogged areas brought forward to form some reduced soils (fine, mixed, thermic, typic haplosalids), which are distinguished by their color and position comparing with neighboring soils with the interpretation of bird's-eye photos (Table 9.2, Fp 211). The gleyic characteristics of these soils are the best evidence of formation of such geomorphic surfaces (Fig. 9.15).

The Zayandeh-Rud River terraces are multidirectional, valuable sediments. They guarantee life in the basin. Balanced distribution and usage of surface and underground water among multiple consumers continue the life of the community on these terraces. Underground water storage capacity will remain constant if the entrance and extraction of water are balanced. This completely depends on the amount of yearly surface water interference and human management programs.

Based on the estimation of Gohari et al. (2013), the impacts of climate change on agriculture in the Zayandeh-Rud Basin, when climate changes to a dryer and warmer position, would be drastic. In such conditions, crop production will decrease, crop irrigation water requirements will increase, growing periods will shorten, and water productivity of all crops will decrease. This induces that crop yield would reduce significantly; therefore, continued cultivation of these locally high-value crops cannot be justified during the current dry period. To reduce its negative economic effects in the Zayandeh-Rud Basin, proper adaptation policies must be undertaken. In such adaptation programs, gray water usage, changing of current crops with environmentally and economically more efficient types, and efficiency enhancement of water productivity and irrigation programs at farm and regional scales should be included.

9.3.9 Wind Erosion

In the early decades of the previous century, there was no sign of wind erosion in the Zayandeh-Rud Basin. There was no record of wind deposition along the river routes. Desert pavement existence on all piedmonts, waterlogging, and good vegetation cover on landforms of basin, especially in the Roodasht area, were the main factors preventing wind erosion from occurring in those times. A few decades later, with the establishment of the Roodasht drainage system, the prevention of water and material flow (through Khoshkeh Rud) to Segzi playa by the building of Shahin Shahr coincided with aggressive domination of drought, water, and moisture of playas vanished, and the green cover from playa surfaces perished accordingly. All of these negative phenomena acted as a vigorous driving force for desertification and playa formation. Consequently, in the eastern part of the valley, salty, loose, and fine-textured material of deserted lands underwent intensive wind erosion (Fig. 9.16). It means that wind erosion started suddenly in the 1960s.

9.4 Conclusion

These sequences of geologic, hydrologic, and geomorphologic processes set such soil infrastructure in the entire study area, which without considering their evolution and cause of formation is hard to describe and interpret the diversities existing in the valley. The phylogenic interpretations help us to understand the geomorphic detail

Fig. 9.16 Recently wind eroded landscape in the Segzi playa (Pl 114)

subdivisions. Regional managers are strongly recommended to consider the landscape evolution and their changing processes to know how to allocate the water resources for different disciplines without increasing the degradation in any point of the system.

This long history of water reduction through geologic time and its ever-changing behavior shows us that drought phenomena will last into future, at least throughout our lifetimes. Through this sequential evolution, it is explicitly obvious that when human activities mingle with natural diversifications, the outcome is more drastic.

A dynamic, comprehensive, and integrated water management system will spatially arrange the distribution and consumption of irrigation water in the basin and especially in the Roodasht region. This program should dynamically involve the yearly change of available water, cropping spatial plan, farmer's economy, cropping extent, playa and salinity expansion, and soil distribution in the considered area.

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Chapter 10
Evaluation of Lead and Cadmium Contamination in the Zayandeh Rud River

Atefeh Chamani

Contents

10.1 Introduction

Despite numerous advantages, human developments have caused profound impacts on ecosystems, especially on aquatic ecosystems that represent vast development potentials. In order to monitor the health and functioning of such ecosystems, the water physicochemical characteristics have shown limited utility as contamination indicators due to their ever-changing nature (Noori et al. 2010). Sediments have been found to be a more reliable and valid indicator of water contamination level. From the perspective of environmental geochemistry, sediments are the most important part of the lithosphere serving as the endpoint accumulation of potentially toxic

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elements in the aquatic environment and even the source of water contamination under specific circumstances (Smedley and Kinniburgh 2002). They have a high capacity to retain pollutants so that approximately over 99% of pollutants throughout the hydrological cycle are found in sediments, while the remaining less than 1% is dissolved in water (Salomons and Stigliani 2012). Sediment contamination with heavy metals (HMs) has captured the concern and scholarly attention of many developing countries around the world such as Iran (Nafchi and Chamani 2019; Zonta et al. 2019; Alahabadi and Malvandi 2018; Bagheri and Azimi 2015; Bahador et al. 2017; Delshab et al. 2017; Haghshenas et al. 2018; Shabankareh et al. 2018). HMs such as cadmium (Cd) and lead (Pb) are likely the most hazardous elements found in the environment (Xue et al. 2017). Some nonessential HMs (microelements) such as Cd and lead Pb are toxic even in tiny concentrations and cause higher toxicity with their increasing concentration (Has-Schön et al. 2015). Pb and Cd are highly toxic for aquatic animals, especially for those standing on higher levels of the food pyramid (Jaishankar et al. 2014). Pb originates from batteries, ammunition, solder, piping, pigments, Pb-based paints, vehicle emissions, insecticide, and alloys (Sayadi and Sayyed 2011; Nezat et al. 2017) and has been implicated in numerous physiological symptoms such as neurological issues, hematological effects, nephrotoxicity, hypertension, and DNA damage through partial deactivation of enzymes (Renieri et al. 2019). Cd is an important and prevalent pollutant in the environment and is found in ores together with zinc, lead, and copper. Exposure to Cd causes several diseases, such as bone loss, osteoporosis, and kidney dysfunction, which ultimately leads to renal failure (Eftekhari et al. 2014; Soylak et al. 2008). The toxicity of Cd may synergistically associate with other toxic elements such as Pb. It is also found that Cd diminishes the absorption of some essential elements such as Zn (Nourouzi et al. 2018). The objectives of the present study were to (1) investigate the Pb and Cd concentrations in surface sediments of the Zayandeh Rud River; (2) compare the resulting Pb and Cd concentrations in sediment with global standards; and (3) assess the contamination level and ecological environmental risk of HMs adopting a number of contamination indices such as bioaccumulation factor, Muller geochemical index (Muller 1969), contamination degree (Hakanson 1980), modified contamination degree, and potential ecological risk index (RI) (Jafarabadi et al. 2017).

10.2 Materials and Methods

10.2.1 Study Area

The Zayandeh Rud River, with a length of more than 350 km (Nabinejad 2018), is the most important river in the central semiarid part of Iran in the Zayandeh Rud River Basin (area coverage of ~41,500 km^2) (Babaei et al. 2013). The river starts from the central Zagros Mountains and ends in the Gavkhuni Wetland (Eslamian et al. 2017) which is about 140 km east of Isfahan City, capital of Isfahan Province

(Mollazadeh et al. 2013). It provides freshwater for municipal, industrial, and agricultural purposes (Hajian and Rahsepar 2010). This river has been subject to extensive wastewater and effluents discharge from several points and nonpoint pollution sources. Considering the distribution of these sources, 12 sites were chosen along the entire length of the river to investigate the concentration of Pb and Cd in the river sediments.

10.2.2 Sampling

The randomized complete block design (RCBD) (Anderson and McLean 2018) was chosen by considering a number of criteria including the distribution of population centers, proximity to sewage and wastewater discharge, and the total length of the river, to select 12 sampling sites, each representing different river conditions. In doing so, the first site was located in the Zayandeh Rud dam lake, 110 km west of Isfahan City (32° 44′ 06.51″ N Latitude 50° 44′ 15.75″ E Longitude). The lake covers an area of 54 km^2 and has a water volume capacity of 150×10^6 m^3 (Shams et al. 2012) which supplies fresh water for municipal, agricultural, and industrial activities in three central Iranian provinces (Hajian and Rahsepar 2010) and runs a 55 MW hydropower plant. The Zaman Khan Bridge, a historic bridge near the small city of Saman (32° 29′ 16.43″ N Latitude and 50° 53′ 54.49″ E Longitude), and (32° 22′ 16.02″ North Latitude and 51° 12′ 15.24″ East Longitude) in the southwest of the province were selected as the second and third sites. These sites represent the upstream mountainous conditions of the river. The remaining sites were distributed in the plain downstream part of the basin after the city of Isfahan from Sharifabad to Shakh-Kenar based on the area of croplands and discharge of municipal wastewaters (especially the Varzaneh wastewater treatment plant) into the river (Fig. 10.1).

10.2.3 Heavy Metal Measurement

An acid digestion method was used to analyze the total metal content (APHA 2005). The concentrations of Pb and Cd in the standard and final sampled solutions were investigated by a Flame Atomic Absorption Spectroscopy Furnace AAS Model 67OG. The metal concentration values were corrected with respect to standard conditions using Eq. (10.1):

$$\begin{aligned}&\text{Metal Concentrations Sediment Samples (mg/kg)}\\&\quad=[\text{Extracted solution Volume}\times\text{Metal Concentrations by FAAS})/\text{Oven}\\&\qquad-\text{Dried Sediment}]\end{aligned}\tag{10.1}$$

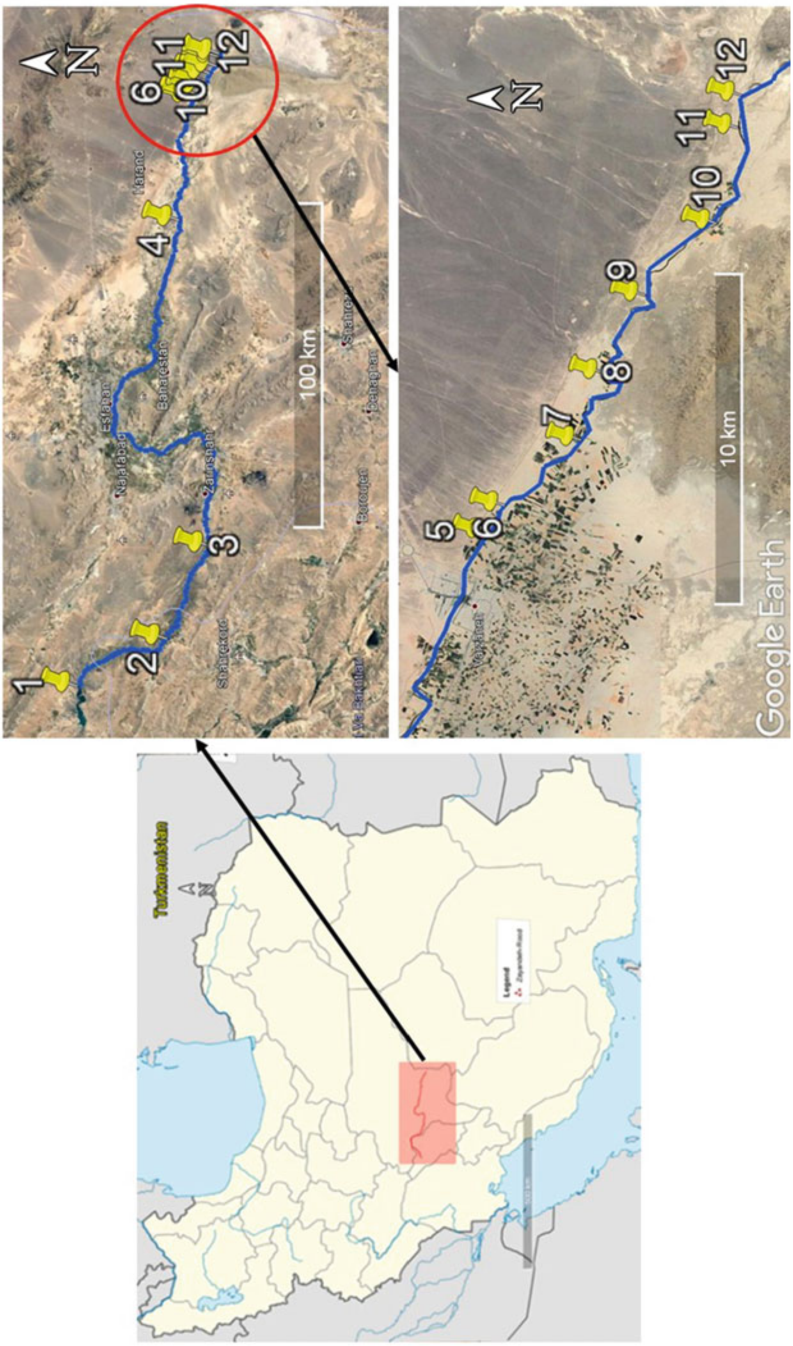

Fig. 10.1 Geographical location of the studied sites

10.2.4 Risk Assessment Indices

10.2.4.1 The Geo-Accumulation Index(Igeo) (Muller 1969)

The Igeo is a globally accepted and widely applied index for examining metal contamination in soil and sediment fractions (Lai et al. 2013; Islam et al. 2015). The Igeo index was calculated using Eq. (10.2) and classified according to Table 10.1:

$$\text{Igeo} = \text{Log2}\left[\frac{Cn}{Bn * 1.5}\right] \tag{10.2}$$

where C_n is the measured concentration of examined metal in the sediment and B_n is the geochemical background value in the Earth's crust (Taylor and McLennan 1995), 14.8 for Pb and 0.1 for Cd (Abrahim and Parker 2008).

The value "1.5" minimizes the effect of the possible variations in the background values which might be ascribed to lithological variations in the sediment.

10.2.4.2 Contamination Factor (CF)

CF is measured by dividing the mean pollutant concentration in the sediments (Mx) by a baseline (background) reference level (Mb) as given in Eq. (10.3):

$$\text{CF} = \frac{Mx}{Mb} \tag{10.3}$$

M_x is metal concentration in the sample, and M_b is the background value in the Earth's crust. It is classified according to Table 10.1.

10.2.4.3 Degree of Contamination (C_d)

The degree of contamination (C_d) is measured as the summation of CFs and gives an estimate of a priori polymetallic contamination for each sampling point (Talbi and Kachi 2019). It is calculated according to Eq. (10.4), and the results are classified into four quality classes (Table 10.2):

$$C_d = \sum\nolimits_{i=1}^{n=3} \text{CF}_i \tag{10.4}$$

Table 10.1 Classification of contamination factor (CF) adopted from Hakanson (1980) and Igeo Muller (1969)

CF degree	CF	Igeo index	Class	Pollution category
Low degree	CF $\leq$ 1	$\leq$0	0	Unpolluted
Moderate degree	1 $\leq$ CF $\leq$ 3	0–1	1	Unpolluted/moderate
Considerable degree	3 $\leq$ CF $\leq$ 6	1–2	2	Moderate
Very high degree	CF $\geq$ 6	2–3	3	Moderate/heavy
		3–4	4	Heavy
		4–5	5	Heavy/extreme
		>5	6	Extreme

Table 10.2 Classification of mC_d adopted from Abrahim (2005) and C_d and Hakanson (1980)

Degree of contamination	mC_d	Degree of contamination	C_d
Very low degree	$mC_d \leq 1.5$	Low degree	$C_d \leq 6$
Low degree	$1.5 \leq mC_d \leq 2$	Moderate degree	$6 \leq C_d \leq 12$
Moderate degree	$2 \leq mC_d \leq 4$	Considerable degree	$12 \leq C_d \leq 24$
High degree	$4 \leq mC_d \leq 8$	Very high degree	$C_d \geq 24$
Very high degree	$8 \leq mC_d \leq 16$		
Extremely high degree	$16 \leq mC_d \leq 32$		
Ultrahigh degree	$mC_d \geq 32$		

10.2.4.4 Modified Degree of Contamination *(mC_d)*

The modified mC_d (Eq. 10.5) index was developed by G. Abrahim and Parker in 2008 to analyze all the parameters used in the C_d index in which "n" is the number of measured metals. The mCd classification is based on Table 10.2.

$$mCd = \frac{Cd}{n} \tag{10.5}$$

10.2.4.5 Potential Ecological Risk Index (RI)

Potential ecological risk index (RI) was first developed by Hakanson (1980) to estimate the degree to which the soil is contaminated by showing the sensitivity of different biological communities to toxic metals (Barkett and Akün 2018) (Table 10.3) (Eqs. 10.6 and 10.7):

$$\mathrm{RI} = \sum\nolimits_{i=1}^{n} E_r^i \tag{10.6}$$

Table 10.3 Classification of potential ecological risk index (RI) and E_r (Hakanson 1980)

Degree of potential ecological risk(RI)	RI	E_r	
Low ecological risk	RI $\leq$ 150	$E_r \leq 40$	Low risk
Moderate ecological risk	150 $\leq$ RI $\leq$ 300	$40 \leq E_r \leq 80$	Moderate risk
Considerable ecological risk	300 $\leq$ RI $\leq$ 600	$80 \leq E_r \leq 160$	Considerable risk
Very high ecological risk	RI $\geq$ 600	$160 \leq E_r \leq 320$	High risk
		$E_r \geq 320$	Very high risk

$$E_r^i = T_r^i \times \frac{M_x^i}{M_b^i} \tag{10.7}$$

E_r^i is the monomial ecological risk factor of metal i.
M_x^i is the concentration of metal i.
M_b^i is the background value in the Earth's crust.
T_r is the toxic response factor of metal i (5 for Pb and 30 for Cd (Jafarabadi et al. 2017).

Foremost among the most useful and universal individual pollution indices is perhaps the I*geo* index, while RI is the most complex index used in this field (Kowalska et al. 2018). Considering such varied indices in this research helps to better evaluate the conditions of the river in terms of HM contamination.

10.2.5 Statistical Method

All data were tested in terms of normality and homogeneity of variance in advance of conducting parametric statistical analysis. Variability among sampling sites was analyzed for each metal by one-way ANOVA. Differences among individual means were tested using the Duncan multiple range test (Van Belle et al. 2004; Thode 2002).

10.3 Results

The mean concentration of Pb in sediments of stations 1 and 2 differed significantly from that of station 6. The mean concentration of Cd was significantly low in stations 1, 2, and 5 while relatively high at stations 8, 9, and 11 (Tables 10.4 and 10.5).

The results of the Muller index (Table 10.6) indicated that all Cd concentrations measured in this research fell within the moderate/heavy pollution groups, while the concentration of Pb was in the range of unpolluted/moderate pollution groups. C_d values showed low/moderate degree at stations 1–6 and considerable degree at stations 7–12.

Table 10.4 Results of ANOVA for Pb and Cd among the stations

Parameters	*F*-value	*P* value
Pb	1.73	0.046
Cd	1.07	0.00

mC_d values showed high and very high degrees of pollution in the studied stations except 1, 2, 3, and 5. CF values of Cd have a considerable and very high degree, whereas those of Pb were moderate. The RI showed low ecological risk at stations 1 and 2, moderate ecological risk at stations 3, 4, and 5, considerable ecological risk at station 6, and very high ecological risk at stations 7–12 (Table 10.6).

Results of one-sample test showed the mean concentrations of Cd outweighed those of ISQG standards (P value < 0.05), while the mean concentration of Pb was within the acceptable ranges of the ISQG standard (P value < 0.05) (Table 10.7).

10.4 Discussion

As shown in Table 10.8, the mean concentration of Cd is by far higher than the findings of studies carried out in different locations in Iran such as Anzali wetland (Shariati et al. 2019), Maharlu Lake (Moore et al. 2019), Takab (Sharifi et al. 2016), Zarshuran (Mousavi et al. 2018), and Alagol wetland (Yousefi et al. 2019).

According to ISQG standards, the mean concentration of Pb in the sediments was acceptable (<35 mg/kg), while that of Cd exceeded the limit values (>0.6 mg/kg).

The concentration of HMs in sediments of aquatic ecosystems may rise due to their deposition into sediment when the surface water evaporates. The high concentration of Pb in river sediments may be rooted in numerous human activities, such as urban effluent discharging, and the geological characteristics of the area. The mean Cd concentrations differed insignificantly between the stations and were by far higher than the ISQG standard (0.6 mg/kg) (Table 10.4). Urban effluents seem to be the main contributor to high Cd concentrations in the sediments because the river is heavily surrounded by a large number of urban and rural areas and industrial centers with their treated and untreated wastewater effluents being discharged into the river. Jalalian (2018) found that atmospheric dust stemming from this region has a high Cd level which further corroborates the high concentration of Cd in the soil and sediments of the wetland.

In the past, all the chemicals and minerals derived from agricultural, domestic, and industrial activities and sediments resulting from human-induced surface soil erosion were transferred into the river channel through surface and underground flows, making the river sediments a major depository of organic and HM pollutants.

Station 1 is the Zayandeh Rud dam lake, which was expected to have a lower pollution load than other stations due to the prevention of wastewater and sewage discharge. The mean concentration of lead at this station is lower than the ISQG standard, but the mean cadmium concentration is within the standard level, and more detailed studies should be conducted to investigate the sources of cadmium. The potential ecological risk (RI) places this area at a low ecological risk degree.

Table 10.5 Duncan's multiple range test (MRT) between stations

Variable	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
Pb (mg/kg) (sediment)	13.5 ± 3.26^{c}	14.9 ± 1.4^{c}	17.6 ± 3.98^{bc}	23.06 ± 5.75^{bc}	22.06 ± 5.29^{bc}	35.18 ± 6.66^{ab}
Cd (mg/kg) (sediment)	0.56 ± 0.06^{a}	0.81 ± 0.06^{a}	1.00 ± 0.17^{ab}	1.12 ± 0.33^{abc}	0.93 ± 0.3^{a}	1.46 ± 0.31^{abcd}
Variable	Station 7	Station 8	Station 9	Station 10	Station 11	Station 12
Pb (mg/kg) (sediment)	18.58 ± 1.22^{bc}	18.58 ± 2.5^{bc}	19.0 ± 1.3^{bc}	20.3 ± 0.79^{bc}	20.25 ± 0.25^{bc}	21.41 ± 0.16^{bc}
Cd (mg/kg) (sediment)	2.08 ± 0.08^{cd}	2.25 ± 0.25^{d}	2.16 ± 0.08^{d}	2.0 ± 0.14^{bcd}	2.16 ± 0.08^{d}	2.00 ± 0.00^{bcd}

Table 10.6 Results of Igeo, CF, C_d, mC_d, E_r, and RI indices measured for Pb and Cd of Zayandeh Rud River sediments

Index	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
Igeo(Pb)	−0.13	−0.28	−0.11	0.07	0.21	0.78
Igeo(Cd)	0.74	1.32	2.06	2.32	1.32	2.74
CF(Pb)	1.38	1.23	1.39	1.57	1.73	2.57
CF(Cd)	2.5	3.75	6.25	7.5	3.75	10.00
C_d	3.88	4.98	7.64	9.07	5.48	12.77
mC_d	1.94	2.49	3.82	4.54	2.74	6.29
E_r(Pb)	6.88	6.16	6.96	8.76	8.66	12.86
E_r(Cd)	75	112.5	187.5	225	112.5	300
RI	81.79	118.66	194.46	232.86	121.16	312.86
Index	Station 7	Station 8	Station 9	Station 10	Station 11	Station 12
Igeo(Pb)	−0.18	−0.20	−0.15	−0.05	−0.05	0.03
Igeo(Cd)	3.79	3.89	3.85	3.73	3.85	3.74
CF(Pb)	1.33	1.33	1.36	1.45	1.45	1.53
CF(Cd)	20.83	22.5	21.67	20.0	21.67	20
C_d	22.16	23.83	23.02	21.45	23.11	21.53
mC_d	11.08	11.91	11.51	10.73	11.56	10.76
E_r(Pb)	6	6	6	7	7	7
E_r(Cd)	625	675	650	600	650	600
RI	632	682	657	607	657	608

Table 10.7 One-sample test to compare Pb and Cd mean concentration with ISQG standard

	Standard	df	*P* value	Mean difference
Pb	35	41	0.00	−14.5
Cd	0.6	41	0.00	0.86

Table 10.8 Mean concentration of Pb and Cd measured in sediments of aquatic ecosystems in Iran

Location	Mean concentration (mg/kg)		References
	Pb	Cd	
Anzali wetland, North of Iran	23.36	0.23	Shariati et al. (2019)
Khiav River, Ardebil Province NW of Iran	13.35	–	Shakeri et al. (2019)
Maharlu saline Lake, southwest Iran	7.42	0.29	Moore et al. (2019)
Po delta lagoons (Italy)	26.9	0.48	Zonta et al. (2019)
Rural rivers in the Taihu Lake region, China	85.4	6.75	Bo et al. (2015)
Southeast coast of Tamil Nadu, India	11.1	3.8	Ravisankar et al. (2018)
Bohai, China	30.98	0.09	Liu et al. (2016)
Alagol wetland, Mazandaran	2.1	0.02	Yousefi et al. (2019)
Zayandeh Rud River	20.48	1.4	This study

A significant rise was observed in the level of river pollutants and ecological risk downstream of Isfahan City, especially after the wastewater treatment plant (stations 7–12), where any water withdrawal for agricultural and livestock purposes significantly elevates the risk of food-chain contamination with HMs. The progressive drying up of the Gavkhuni wetland, as the ultimate repository of pollutants in the region, indicates the imminent creation of a dangerous HM-contaminated atmospheric dust. It is projected that the concentrations of HMs in dust rise 2–3 times the current levels by the complete drying up and conversion of the Gavkhuni wetland into a dust source, with the potential to affect larger spatial ranges. A land use change study by Jalalian (2018) showed that the area of rangelands decreased by half during a 15-year time period at the expense of increasing salt lands from 13.7 to 17.5% of the region which resulted from consecutive droughts and the consequent abandonment of agricultural fields and with the high potential to act as Cd- and Pb-rich dust sources. These findings raise an alarm about the condition of the Zayandeh Rud River, as the only permanent river in the central plateau of Iran which provides freshwater to three arid central provinces in Iran.

10.5 Conclusion

The concentrations of HMs measured in this study significantly outweighed those of other studies carried out in the aquatic ecosystems of Iran and the rest of the world. The mean concentration of Pb in the sediments was below the international standards, while the mean concentration of Cd in the sediments in the studied stations was significantly higher than the ISQG standard. Our findings highlight the critical condition of the river as the most important source of freshwater in the central Iranian Plateau. In addition, this study could serve as a basis for targeting policies toward the reduction of HM accumulation in aquatic environments. From a methodological point of view, this study underscored the usefulness of chemical pollution indices in representing the spatial distribution of HMs. In addition, this study could serve as a basis for targeting policies to reduce heavy metal and protect sediment from the accumulation of heavy metals over time. Moreover, strict management practices need to diminish or prevent discharge of poorly treated effluents into the river.

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Chapter 11
Dust Production Crisis Following the Recent Droughts in the Eastern Part of the Zayandeh Rud River Basin

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11.1 Introduction

Wetlands have various advantages to the planet, duo to high productive, distinctive as well as biologically diverse ecosystems. Approximately, 6% of the world's land surface is covered by these natural ecosystems and has several significant benefits for human society including the improvement of water quality, flood reduction biodiversity conservation, and the storage of water (Cui et al. 2009). In recent decades, the consequences of fast population growth and the surface water extraction for supplying public water, agriculture, and industry water have caused a great reduction in wetlands water availability, and endanger the health and survival of these natural ecosystems, particularly, in arid and semiarid regions (Acreman et al. 2007; Jia and Luo 2009; Sarhadi and Soltani 2013). The wetland's inflow interruption caused by severe drought conditions, destroys their ecological functions, and affects their hydrological regime in the regions of arid and semi-arid.

The Gavkhuni wetland is located in the arid region of central Iran (52° 39′ E 32°25′ N). In 1975, the Gavkhuni wetland was registered in the international Ramsar convention as a valuable aquatic ecosystem (http://www.ramsar.org). This natural ecosystem is located at the outlet of the Zayandeh Rud river in the eastern part of the Zayandeh Rud basin, with an area of 47,000 ha. The Gavkhuni wetland plays a vital role in the sustainable development of this region. From a conservation viewpoint, it is one of the most valuable ecosystems in Iran, providing habitat for over 140 bird species and several other flora and fauna. In addition, this ecosystem has an effective role in water refinement and the stabilization of sand dunes located in the western parts of the wetland. Unfortunately, improper water resources management and recent population growth have caused a substantial decline in the quality and quantity of the wetland's water and the destruction of this natural ecosystem has begun. Also, unfair water resources transmission and the diversions upstream of water have led to reduced inflows downstream and, undesirable ecological impacts on the wetland. On the other hand, the wetland's water quality has influenced by the excessive input of Isfahan untreated domestic and industrial wastewater. In recent years, these disasters have increased by drought which is the consequence of climate change. These harmful situations changed the hydrological regime of the Gavkhuni wetland and consequently, changed it into a salt pan. Figure 11.1 illustrates pictures of this natural ecosystem in the past (Fig. 11.1a) and at the present (Fig. 11.1b).

The consequences of a dried-up Gavkhuni wetland could be classified into social, ecological, economic, and health problems. The main problem appears to be the salt desert with an area of 47,000 ha which is covered with a thick salt deposit. When drought happens, the wind would carry these salts, chemicals, heavy metals, fertilizers, and pesticides deposited in the wetland basin to other areas even a long way away. These materials could damage agricultural lands, infect the ecosystem, and cause a variety of diseases in affected rural and urban areas, especially Isfahan city.

The environmental contamination has not been previously assessed or investigated in the vicinity of the almost dried up Gavkhuni wetland. Thus, it was necessary to carry out an investigation in terms of heavy metals in the atmospheric dust of the

(a)

(b)

Fig. 11.1 The international Gavkhuni wetland condition in the past (Imna 2019) (**a**) and at 2013 (**b**) study area. The main objectives of this study were to (1) investigate the spatial distribution of soil properties, (2) determine the spatial variations of heavy metals deposition rates in samples collected from the vicinity of the Gavkhuni wetland, and (3) compare heavy metal concentrations among atmospheric dusts, Gavkhuni wetland sediments, and soil surface in the study area. Furthermore, the main query we were looking for was whether the annual dusts produced in the area were affected by the dry sediments of the Gavkhuni wetland.

11.2 Material and Methods

11.2.1 Study Area

The study was conducted in the Gavkhuni sub-basin (31° 51′ to 32° 45′ N, 52° 31′ to 53° 21′ E) with an area of 3616 km^2, located in the eastern part of Zayandeh Rud basin, Central Iran (Fig. 11.2a). The international Gavkhuni wetland sub-basin, located at the outlet of the Zayandeh Rud river, occupies approximately 472 km^2 of the basin area. The altitude average of this sub-basin is 1549 m a.s.l. According to the Köppen classification, the study area is classified as a dry climate. The mean annual precipitation and temperature are 94.23 mm and 16.9 °C, respectively. The soil temperature and moisture regimes are thermic and aridic, respectively, and soils are dominantly Aridisols (Soil Survey Staff 2014). The landscapes of the Gavkhuni wetland sub-basin include mountain, hill, plateau, and piedmont. The mean wind

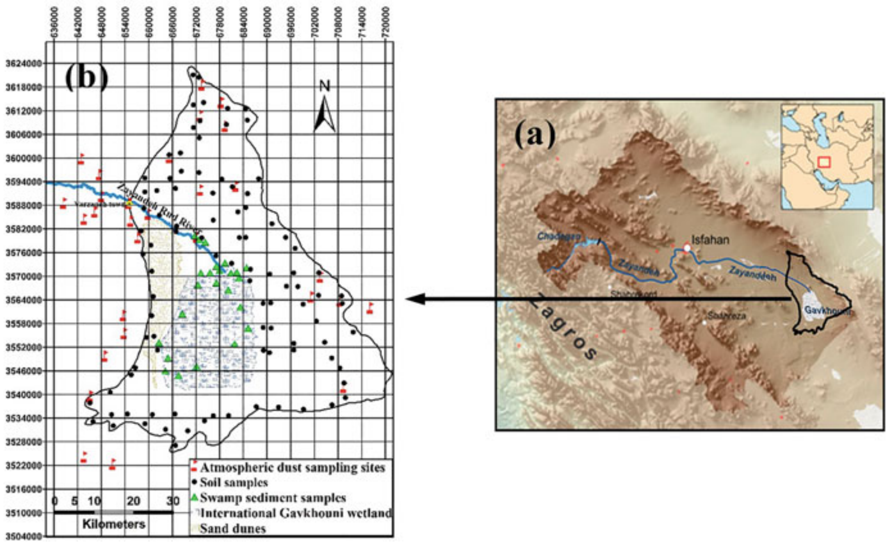

Fig. 11.2 The location of the Gavkhuni wetland sub-basin (**a**) and the spatial distribution maps of surface soil, wetland sediment, and atmospheric dust sampling points (**b**)

speed was 2.9 m/s during the sampling period while the annual prevailing wind directions were E (17.2%), W (12.4%), and NE (10.8%).

11.2.2 Sample Collections

11.2.2.1 Soil Samples

Random sampling within blocks method was used to collect soil samples in the study area. The Gavkhuni sub-basin with the area of 3616 km^2, was divided into 100 blocks of 6×6 km^2 and surface soil samples were taken randomly in each block from 0 to 10 cm (Fig. 11.2b). The GPS was used to record geographical position of sampling points.

11.2.2.2 Wetland Sediment Samples

Due to the severe obstructions (like no access to the road, difficulty of sampling, etc.), the sediment sampling at the wetland was randomly carried out from 24 points at depths of 0–15 cm (Fig. 11.2b).

11.2.2.3 Dust Samples

Atmospheric dust samples were collected using a glass surface (100 cm $\times$ 100 cm) covered by a PVC net (2 mm mesh opening) in order to trap the dust particles (Menendez et al. 2007; Hojati et al. 2012; Norouzi et al. 2015) (Fig. 11.3). The collection tray at each site was placed on the roof of a one-floor building at about 3–4 m above the ground. Atmospheric dust sampling was carried out at 31 sampling sites from October 2013 to September 2014 (Fig. 11.2b). Atmospheric dust samples were collected into the clean plastic cans. The collecting cans were sealed in the field with plastic covers and transferred to the laboratory.

11.2.3 Sample Analysis

Soil analysis included electrical conductivity (EC) (Rhoades 1982) and pH (Lean 1982) in saturated-paste extract; $CaCo_3$ (Allison and Moodie 1965) and gypsum (Artieda et al. 2006). Heavy metals (Cu, Co, Ni, Cd, Cr, Pb, Zn, and Mn) were measured using an atomic absorption spectrophotometer (Perkin Elmer AAS 800) based on the method described by Soon and Abboud (1993). Furthermore, identification of minerals found in dust samples, surface soils, and sediment sampled from

Fig. 11.3 A glass tray (100 cm × 100 cm) covered by a 2-mm PVC net mesh used for dust collection

the Gavkhuni wetland was carried out in powder form using X-ray machine (Kittrick and Hope 1963).

Dust deposition rate (DDR) was calculated according to Eq. (11.1) (Hojati et al. 2012):

$$DDR = \frac{\text{Mass of atmospheric dust}}{\text{Trap area} \times \text{Sampling period duration}} \tag{11.1}$$

11.2.4 Data Analysis

The statistical SPSS software (IBM Corp 2015) was used for the statistical analyses. The maps of annual spatial variations of atmospheric dust deposition rates as well as the atmospheric dust deposition rates of heavy metals were generated by the Inverse Distance Weighting (IDW) method using Arc GIS 10.1 (ESRI 2012).

To determine spatial patterns and preparing the soil properties prediction maps, the Geostatistics technique was employed. For this purpose, the data were first examined for the presence of trends. The semivariogram analyses were also carried out on the soil variables prior to the application of ordinary kriging interpolation to determine the best semivariogram model for the interpolation function. A semivariogram is evaluated by the below equation (Goovaerts 1999):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i + h) - Z(x_i)]^2 \tag{11.2}$$

where $\gamma(h)$ is the semivariance used for the interval class h, $Z(x_i + h)$ and $Z(x_i)$ are two sample values by the distance h. $N(h)$ is also the number of sample value pairs in the distance interval h. Then the variogram can be fitted by using various models (Gaussian, Exponential, and Spherical) (Webster and Oliver 2007).

A variogram is defined by permitted theoretical models and three factors of sill (the lag distance among measurements at which one value for a variable does not have an impact on the values of its neighboring), range (the distance that values of one variable become spatially independent of another one), and nugget (the variance at zero distance). For choosing the best fit with the data, various semivariogram models were evaluated. Finally, the Gaussian, Exponential, and Spherical models were fitted to the experimental semivariograms.

The ratio between the sill and the nugget semivariance was used to specify the degree of spatial dependence (DSD) for the soil parameters. If the ratio was less than 25%, the variable was regarded as having strong spatial dependence or strongly distributed in patches. If the ratio was between 25 and 75%, the soil variable was assessed having moderate spatial dependence; if the ratio was greater than 75% the soil variable was assumed to have weak spatial dependence and eventually if the slope of the semivariogram was near to zero or the ratio was 100%, the soil variable was considered non-spatially correlated (pure nugget) (Francisca et al. 2002).

To select the suitable semivariogram models for comparison of semivariogram models and the statistical values estimated from the actual values, the cross-validation method was used. Experimental and estimated values differences were summarized using the cross-validation statistics which is written as follows:

Root mean square error (RMSE) reveals how closely the measured values and the model predicts are; and is expressed as:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} [z^*(x) - z(x)]^2}{n}} \tag{11.3}$$

As a criterion, the G-statistic (goodness-of-prediction (G-value) estimate) was applied to test model fit efficiency compared to the model fit which could have been derived from using the sample average alone (Agterberg 1984):

$$G - \text{value} = \left(1 - \left\{\sum_{i=1}^{n}[z(x) - z^*(x)]^2 / \sum_{i=1}^{n}[z(x) - \bar{z}]^2\right\}\right) \quad (11.4)$$

where $z(x)$ is a measured value, $z^*(x)$ is a predicted value, $\bar{z}$ is the observed values average, and n is the observation number. A G-value equal to 100% indicates perfect prediction, whereas negative values show that the predictions are less dependable than if sample average was employed instead (Schloeder et al. 2001).

For soil variables spatial interpolation, the ordinary kriging was selected as the preferred method. It was more reliable than the other interpolation methods according to the mean squared error which compares the measured and predicted values. In addition, in the situation of relatively low density of the soil sampling, ordinary kriging seems to be the best impartial predictor at random unsampled locations (Cressie 1993). Minimizing the outliers influence, is the other superiority of ordinary kriging (Triantafilis et al. 2001). Kriged maps making, the geostatistical analysis, fitting the best semivariogram model, and related components (sill, range, and nugget) were carried out by Arc Map (version 10.1) (ESRI 2012).

11.3 Results and Discussion

11.3.1 Geostatistical Analysis

The semivariogram analysis determined spatial dependence classes for the studied soil properties and distinct spatial distribution models (Table 11.1). The $CaCo_3$ fitted with a Spherical model whereas gypsum was fitted by a Gaussian model. The other soil parameters were fitted to the Exponential model. The semivariograms indicated strong spatial dependence (DSD $\leq$ 25%) for pH, EC, and $CaCo_3$; whereas gypsum showed moderate spatial dependence (25 $<$ DSD $\leq$ 75%) (Table 11.1). The strong spatial dependence of soil properties might be due to the natural factor influences, such as hydrological processes and strong pedological, climate, the parent material, and soil-forming factors, and soil type in the studied area (Aghasi et al. 2017). However, the moderate spatial dependency may show that the anthropogenic factors may change the soil's spatial correlation through farming, management practices, industrial production, and other human activities (Yang et al. 2009).

The range values showed a large variability among the soil parameters which can be a useful principle for the mapping of soil parameters (Utset et al. 1998; Fu et al. 2010). Table 11.1 indicates that the spatial correlation of soil properties (range) widely varied from 19.4 (for pH) to 74.5 km (for EC). The different ranges of the spatial dependencies among the soil properties may be due to differences in land cover, erosion–deposition factors, parent material as well as topography in the study area (Tesfahunegn et al. 2011). A large range shows that the observed values for the soil parameters are affected by other more distance values of this parameter compared to the soil parameters with smaller ranges (Lopez-Granados et al. 2002).

Table 11.1 Semivariogram models, interpolation parameters, and cross-validation statistics of selected soil properties in the study area

			Range (km)						Cross-validation statistics	
Variable	Model	Direction (angle)	Major	Minor	Nugget	Sill	DSD (%)	Spatial dependence class	RMSE	G (%)
$CaCo_3$[a]	Spherical	80.3	47.7	24.4	0.02	0.09	24.6	Strong	4.75	77
pH	Exponential	161.3	19.4	8.2	0	0.21	0	Strong	0.38	50
EC[b]	Exponential	145.9	74.5	40.1	0.04	0.27	14.27	Strong	0.33	52.52
Gypsum[a]	Gaussian	150.3	56	28.8	1.17	1.98	59.1	Moderate	2.19	10.16

DSD degree of spatial dependence, EC electrical conductivity, G goodness-of-prediction estimate, RMSE root mean square error

[a]Log normal

[b]$(\mathrm{Log})^{1/2}$ normal

Hence, a large range of 74.5 km for EC implies that EC values influenced neighboring values of EC over greater distances than the other soil variables.

The cross-validation statistics demonstrate how well soil properties can be estimated by application of the ordinary kriging method. Such tests were checked with the RMSE values and the models with the lowest RMSE value were selected as shown in Table 11.1. These low values imply that kriging predictions of soil parameters are closer to the measured values. Furthermore, to evaluating the accuracy of kriged soil properties spatial maps, the G-value was utilized (Table 11.1). The value of the G-parameter indicates the prediction capacity of the datasets for employing kriging from the sample points as compared to sub-basin average values. The kriging model had the best performance for $CaCo_3$, EC, and pH with G-values of 77, 52.52, and 50, respectively. Moreover, it performed moderately well for the gypsum.

11.3.1.1 Spatial Distribution of Soil Properties

Figure 11.4 illustrates the interpolation maps for some studied soil properties. The prepared maps for the $CaCo_3$, gypsum, and EC parameters show that these parameters are greater in the western and southwestern parts than the other areas. This could be due to the natural parameter impacts such as parent materials (in the southwestern and western parts, marl, and limestone parent materials are dominant). Additionally, the low level of groundwater around the Gavkhuni salt marsh and the high evaporation in this area might also lead to accumulation of soluble salts and evaporite minerals such as calcite, gypsum, and halite in these regions (Aghasi et al. 2017). However, due to the lower solubility of gypsum, the content of this parameter was lower than the other soluble salts and evaporate minerals in the soil surface. The high level of soluble salt concentrations in sediments of Gavkhooni salt marsh, lead to adjust of the pH below 8 in southwestern and western parts of the study sub-basin.

11.3.1.2 Spatial Distribution of Dust Deposition Rates

Figure 11.5 shows the spatial distribution of the Dust Deposition Rates (DDR) in the study area. The annual deposition rates of dusts range from 7.04 to 220.53 ton km^{-2} $year^{-1}$ with an average annual value of 46.1 ton km^{-2} $year^{-1}$. Considering the spatial distribution of mean annual DDR values, it is depicted that the deposition rate in the western parts of the study area is greater than the other parts (Fig. 11.5). The main reason for this could be the prevalence of the eastern wind in the region as well as the presence of sand dunes in the western parts which could have resulted in an increase in the high deposition rates of sand particles in these areas due to the heavy nature of the particles. The type of particles that are displaced by wind depends on the wind speed and those particle sizes. Coarser particles are more slowly transmitted by wind than smaller particles. Also, the coarse particles are deposited on the ground surface after a few hours (AL-Harbi 2013).

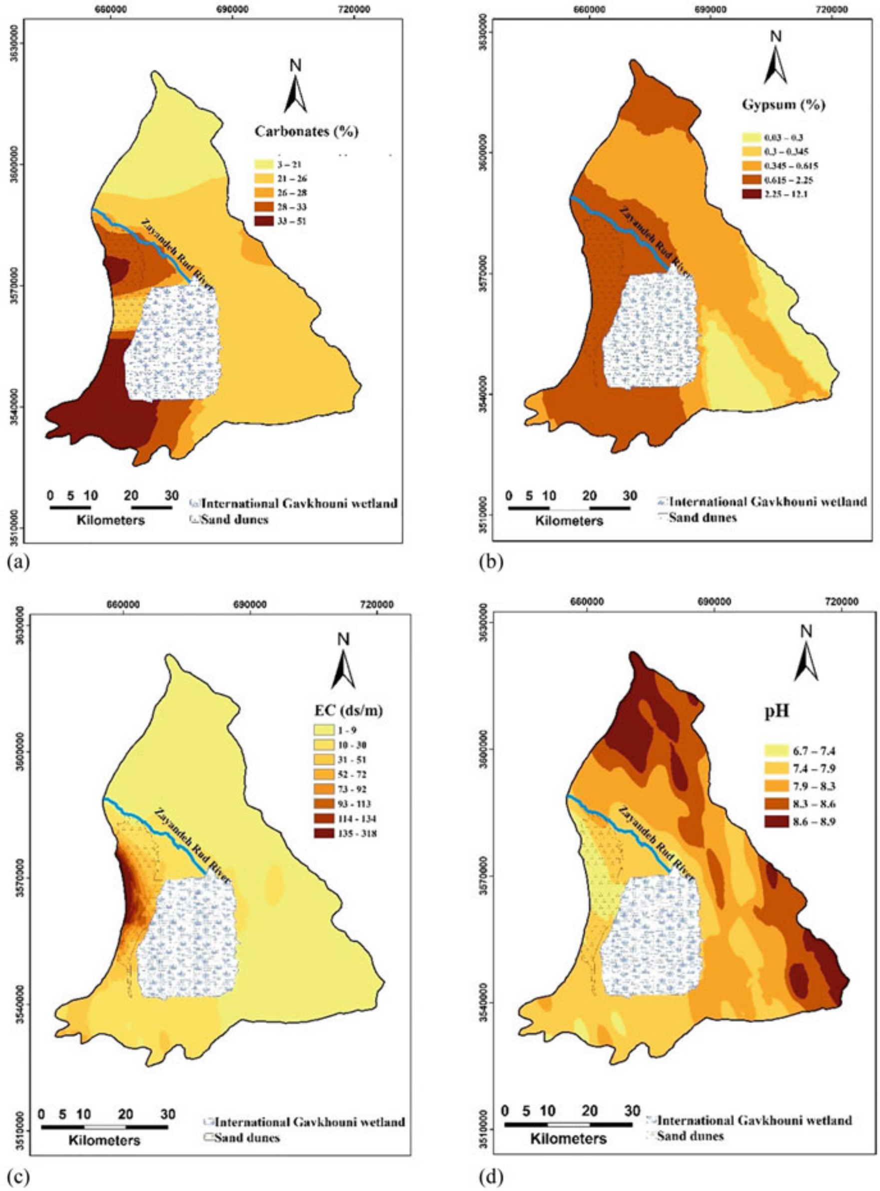

Fig. 11.4 Spatial distribution of selected soil properties interpolated using ordinary kriging for the Gavkhuni sub-basin

By comparing the average rates of dust deposition in the study area with the other parts of the world (Table 11.2), it can be said that the DDR in our study area (which includes wetland, desert, and rural areas) is more than that in rural areas, but

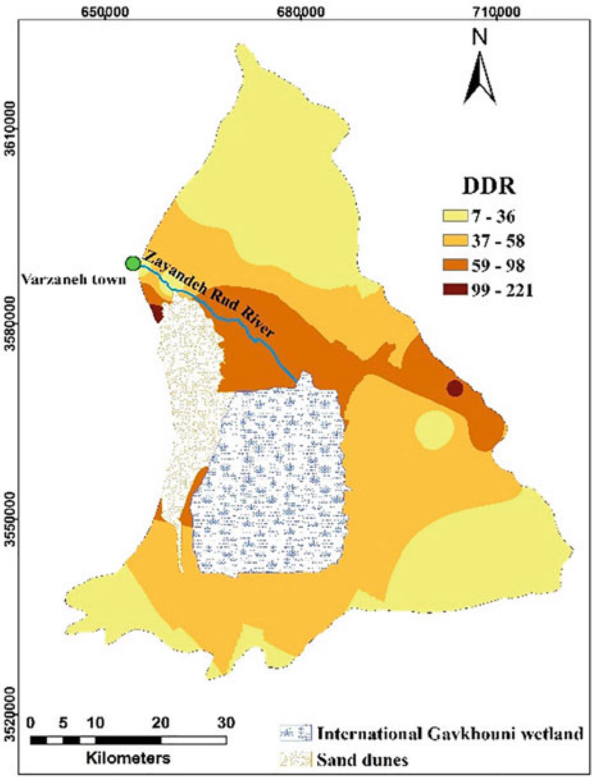

Fig. 11.5 Mean annual spatial variations of atmospheric dust deposition rate (DDR) in the study area (ton km^{-2} year^{-1})

relatively lower than in urban areas. One reason for this finding would be the presence of dust-producing human activities such as being in high traffic as well as proximity to areas with civilian operations. In a similar study, Wang et al. (2015) reported that the DDR in the southwestern and northeastern parts of Beijing city, and during spring, was greater and stated that the mountains in the northwestern part of the city had the lowest levels of dust deposition. They also concluded that the dusts originated from the soil surface, coal, vehicles, and construction dusts are the four main sources of dust deposition in cities. Jafari (2013) attributed the highest amount of atmospheric dust deposition in the city of Kerman (southwest Iran) to the central, north and northwest parts of the city, and stated that the possible reason for this was construction activities in the city center.

11.3.1.3 Deposition Rate of Heavy Metals

Manganese had the highest annual deposition rate among the investigated heavy metals with an average of 16,552 g km^{-2} year^{-1} followed by zinc and lead with an annual deposition rate of 7324 and 1836 g km^{-2} year^{-1}, respectively. Furthermore,

Table 11.2 Atmospheric dust deposition rates (ton km^{-2} $year^{-1}$) reported for different areas

Location	Study area	Deposition[a]	Ref.
Penny Ice Cap	Ice Cap	0.05	Zdanowicz et al. (1998)
Miami, Florida, USA	Urban	(0.1–1.26)	Prospero et al. (1987)
Sapporo, Japan	Rural	5.20 (0.8–21)	Uematsu et al. (2003)
Thessaloniki, Greece	Urban	6.04	Anatolaki and Tsitouridou (2007)
Eastern Australia, Australia	Rural	(31.4–43.8)	McTainsh and Lynch (1996)
Dead Sea, Israel	Rural	44.5 (25.5–60.5)	Singer et al. (2003)
Gavkhuni sub-basin	Wet land/desert/ rural	46.1 (6.96–221.52)	This work
Phoenix, Arizona, USA	Rural	54.5	Pewe (1981)
Qingdao, China	Urban	(36.5–58.4)	Zhang et al. (2004)
Aliaga, Izmir, Turkey	Industrial	103.7 (19.3–300.4)	Kara et al. (2014)
Taichung, Taiwan	Urban	211	Fang et al. (2007)
Taklimakan Desert, China	Desert	450 (110–1900)	Zhang et al. (1998)

[a]Mean value with the range in parentheses

nickel, chromium, copper, and cobalt had an average annual deposition rate of 1693.4, 11.55, 9.882, and 6.301 g km^{-2} $year^{-1}$, respectively. The lowest annual deposition rate belonged to cadmium with an average of 9.95 g km^{-2} $year^{-1}$. On the other hand, the highest annual deposition levels of the two lead and zinc elements were observed in the western part of the study area and a decreasing trend in the deposition rate of these elements to the eastern parts of the region was detected. The annual deposition rate for cadmium and cobalt elements is similar and the highest values are observed in the western and central parts of the study area. The spatial distribution maps of the annual atmospheric deposition rate of nickel, manganese, copper, and chromium also show that these elements have the greatest deposition rates in the western and eastern parts (Fig. 11.6). In addition, since the spatial distribution maps of the annual deposition rate of heavy metals for the region are similar to those of the annual deposition rate of dusts in the study area, it appears that the spatial distribution of heavy metals in the study area is largely affected by the dust deposition rate in the region and is thus less dependent on the spatial distribution of the mean concentration of these elements in the region.

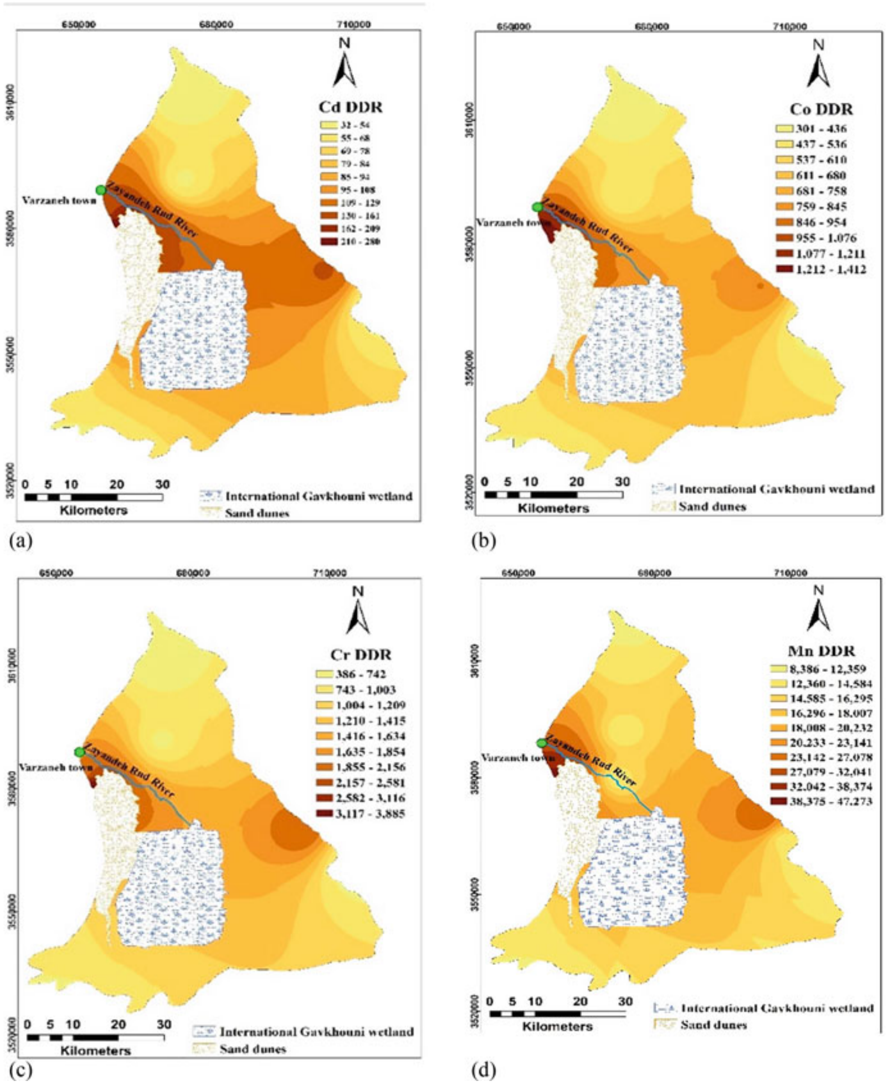

Fig. 11.6 Annual spatial variations of atmospheric dust deposition rates of heavy metals (g km^{-2} $year^{-1}$) in the study area

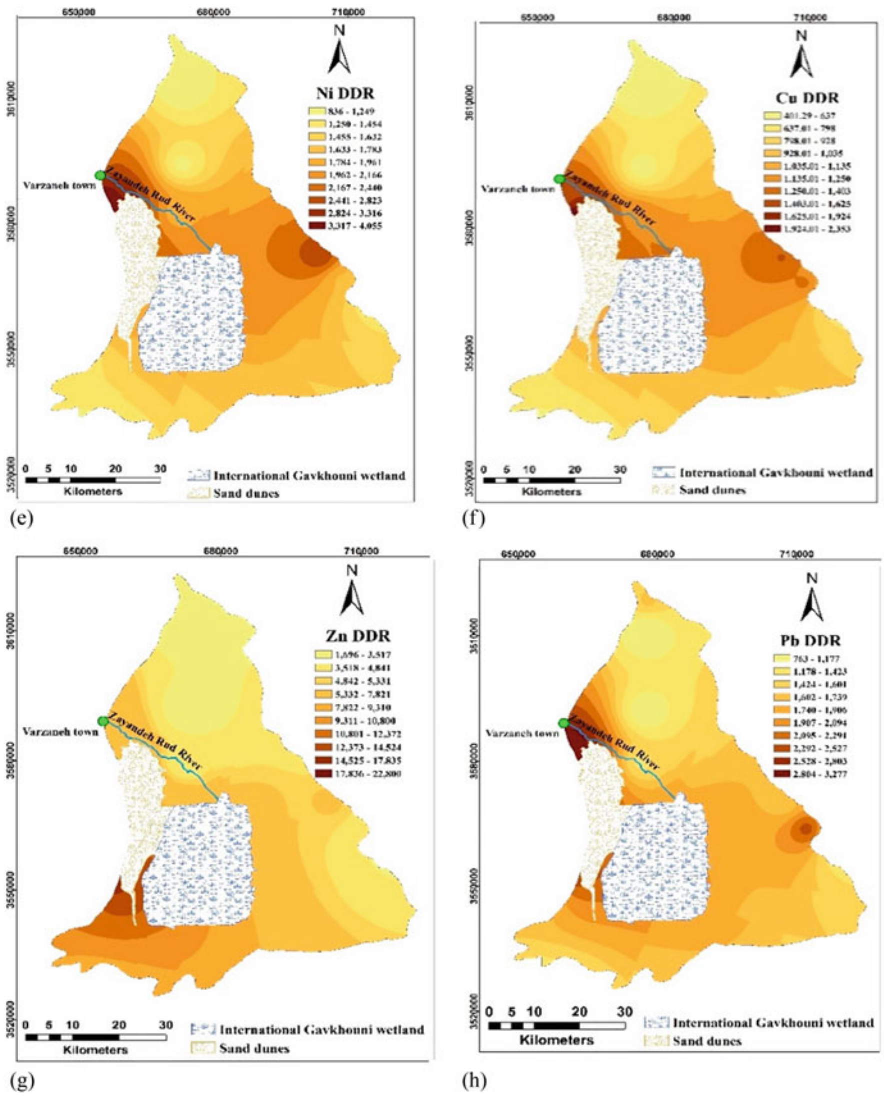

Fig. 11.6 (continued)

11.4 Comparison of Heavy Metal Mean Concentrations in Dust, Gavkhuni Sediment, and Surface Soil

A comparison of the mean concentration of heavy metals in sampled dusts, wetland sediments, and surface soil in the study area indicated that most of the heavy metals in the dust samples contained greater concentrations of heavy metals in comparison with wetland sediments and surface soil due to their higher specific surface area (Fig. 11.7). However, the greatest concentration of cadmium (Cd) was observed in

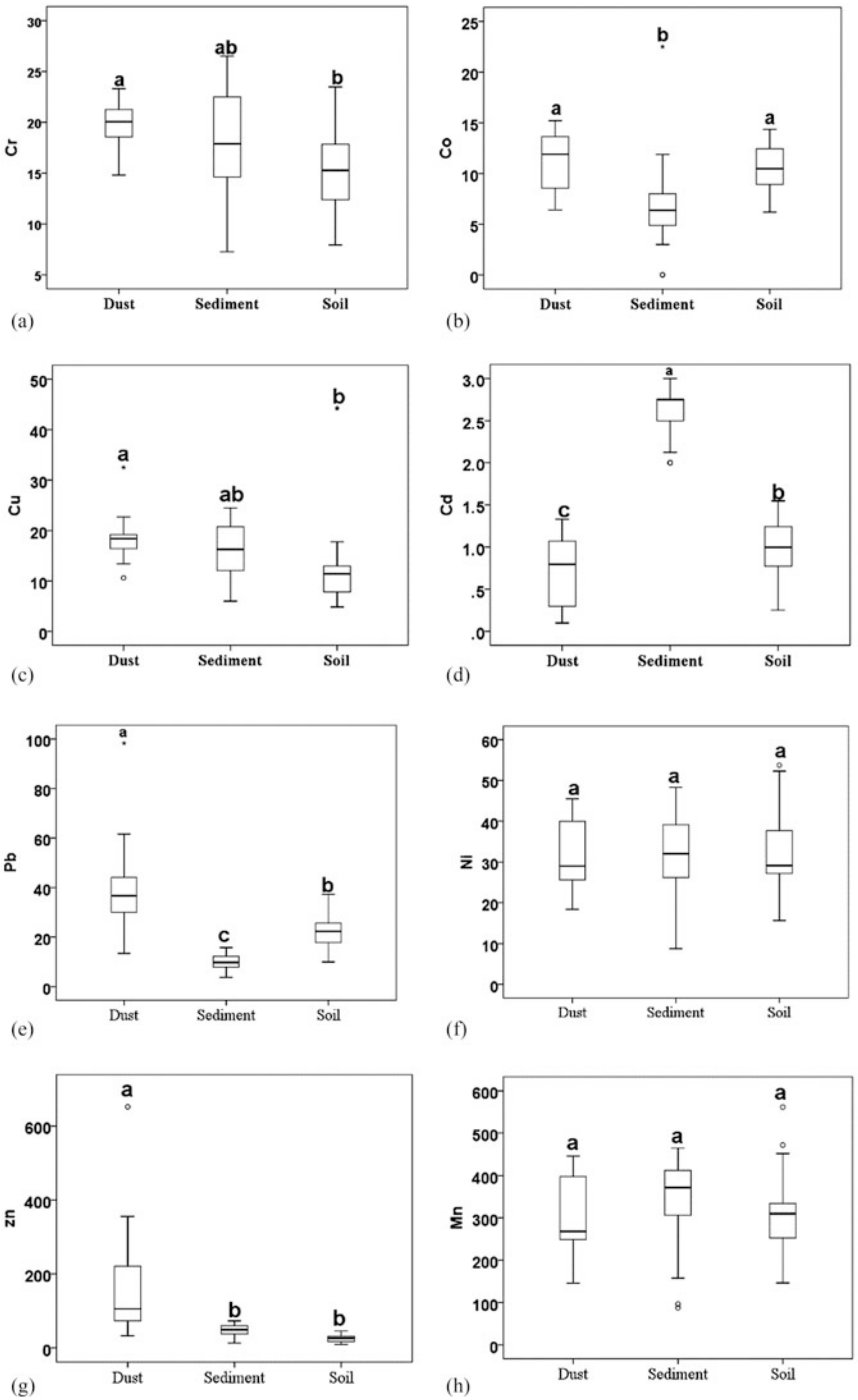

Fig. 11.7 Box plots of annual mean heavy metal (mg kg^{-1}) for selected elements in dust, Gavkhuni sediments, and surface soil (Means with similar alphabets do not have a significant statistical difference at 0.05 Duncan's test.). The horizontal line in a box indicates the median, and the lower and upper ends of a box indicate the 25th and 75th percentiles, respectively (asterisk: extremelier and open circle: outlier)

wetland sediment samples. Agricultural pesticides and drainage from agricultural lands in the lower part of the Zayandeh Rud basin mainly entered into the Zayandeh Rud river and eventually flowed into the Gavkhuni wetland. Consequently, the Cd concentration may have increased in the sediments of the wetland. Several researchers have reported that numerous human activities, such as irrigation with wastewater, as well as the use of organic fertilizers and phosphates, may lead to the release of significant amounts of Cd into the environment (Javied et al. 2009; Wei et al. 2009). Additionally, pesticides are another source of cadmium (Singh et al. 2011).

11.5 Identifying the Potential Source of Dusts in the Study Area

Different physical, chemical, isotope, and mineralogical methods could be used to determine the regions producing atmospheric dust. Dust particle size distribution is also a good indicator of the origin of these particles as well as their transmission distance. For example, the existence of Multilingual Distributed Patterns (MDP) represents dust particles with different origins or the effect of different processes on the transfer of these particles (McTainsh et al. 1997). Furthermore, the similarity of Ti/Zr and Si/Zr ratios in dust samples with the ratio of these elements in sediments or surface soils of the region can increase the likelihood of the origin of dust particles from these sources (Hojati et al. 2012). In this study, the frequency of fine sand fraction in collected dust samples indicates the regionality of the dusts (Lawrence and Neff 2009). In addition, due to the similarity of the type and abundance of minerals in dusts to those in the surface soil of the study area (Fig. 11.8) and the close average values of Ti/Zr and Si/Zr ratios (Table 11.3), as well as the particle size distribution of the sampled dusts and the soil surface in the region (Table 11.4), it appears that the dust productions in the study area is affected by the surface soil of this region. The particle size distribution class of the dusts is loam which is usually observed in cases where the dust particles are transmitted from low to medium distances (Lawrence and Neff 2009). Sand particles in the wetland sediments have the least abundance while the surface soil in the region contained greater sand content. In addition, due to the presence of moisture in the surface sediments of the wetland (2–57%), the Gavkhuni wetland is not likely to enter the dust production cycle.

In a similar study, Mahmoudi (2011) investigated the characteristics of subsurface dusts in Isfahan. Considering the similarity of chemical characteristics and mineralogy of dust with the soils of the eastern region of Isfahan, as well as the pattern of wind direction and particle size (which indicates the average distance to the time of transfer of particles), he concluded that the eastern parts of Isfahan province are the main source of Atmospheric dusts. Karimzadeh (2002) also studied the source of wind erosion sediments in the eastern region of Isfahan. The results of

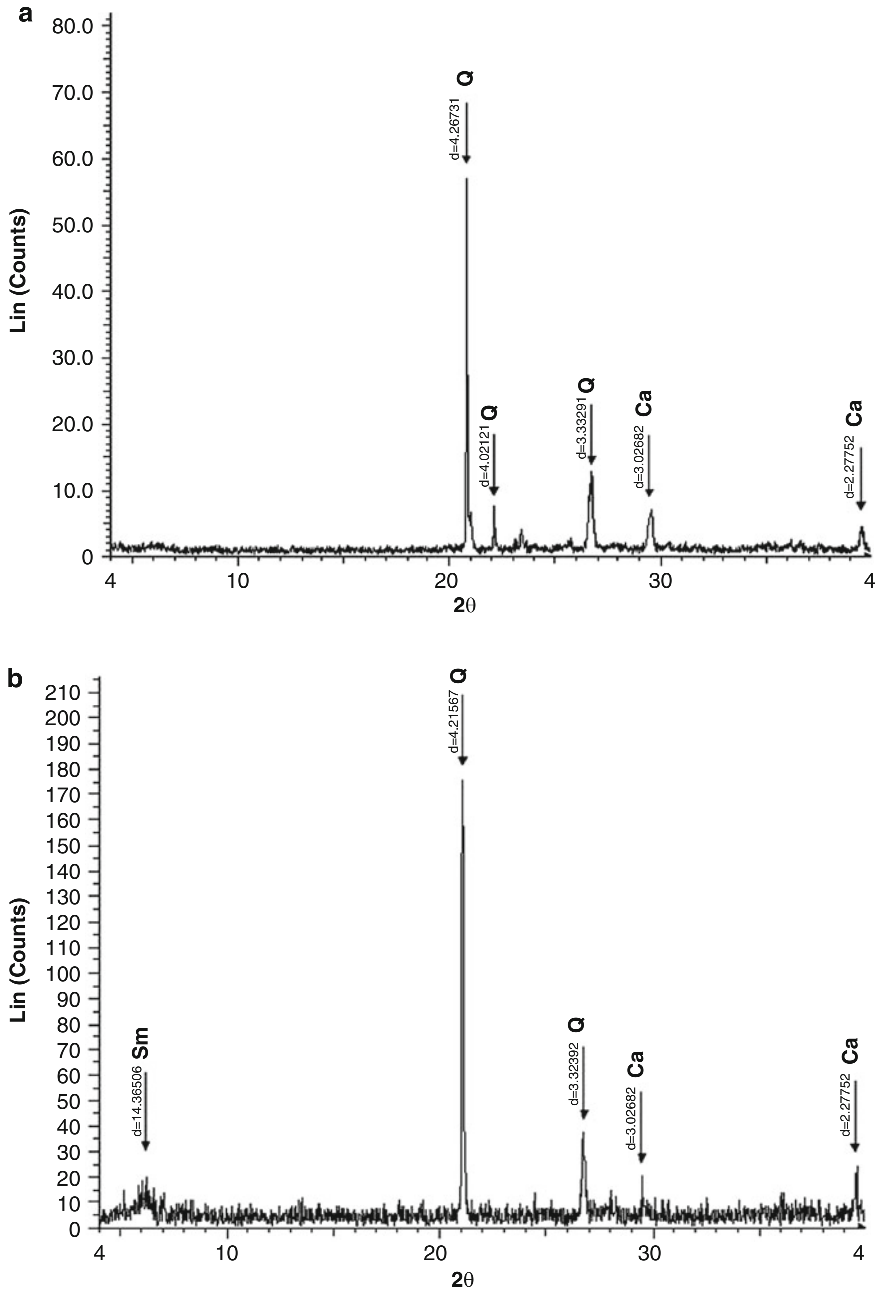

Fig. 11.8 Diffractograms of powdered samples for dust samples (**a**), surface soil (**b**), and Gavkhuni wetland sediments (**c**). *Q* quartz, *Ca* calcite, *Sm* smectite, *Dol* dolomite

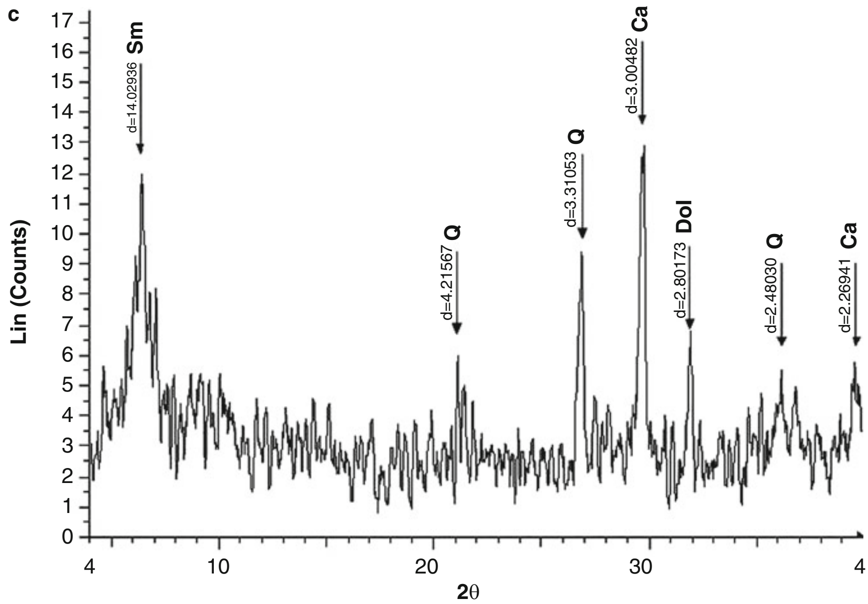

Fig. 11.8 (continued)

Table 11.3 The average of Ti/Zr and Si/Zr in the atmospheric dusts, surface soil, and wetland sediments

Parameter	Atmospheric dusts	Surface soil	Wetland sediments
Ti/Zr	61.61	55.7	43.17
Si/Zr	5896.5	5333.6	3554.5

Table 11.4 Average particle size distribution of atmospheric dust, wetland sediments, and surface soil in the study area

Parameter	Sand	Silt	Clay	Texture
	(%)			
Annual dust	47.69	30.88	21.44	Loam
Wetland sediments	27.1	34.3	38.6	Clay loam
Surface soil	75.7	11.9	12.4	Sandy loam

particle size distribution, concentration of various elements (especially the rare elements), as well as the morphoscopic indices revealed the localization of dust ablation areas. In addition, his mineralogical studies confirmed the localization of the dust origins as well as the close relationships among mineralogical studies and the wind erosion sediments, old eroded surfaces, and adjacent alluvial deposits. Other similar studies have also shown that the coarser dust particle size distributions indicate the shorter distance between the deposition sites and the dust sources (Lawrence and Neff 2009). Due to the fact that the coarse particles in the dust fall at the very beginning of the dust suspension, dust tends to be smaller by distance from their origin (Goudie and Middleton 2006). Singer et al. (2003), by the use of the particle size distribution analysis, found that their studied dusts have transmitted from medium to long distances. Pye (1992) showed that dust particles rich in quartz, carbonate, and feldspar minerals are of continental origin and are likely to be transported from regions close to or relatively close to the dust collecting site. In contrast, dusts with higher clay minerals are transported from distant areas. In addition, the Paleygorskite is one of the rare minerals that can be seen in some dry soils and semiarid regions depending on the geochemical conditions (Singer 1989). Therefore, the presence of this mineral in dust samples can be used as a means of identifying the origin of dusts (Singer et al. 2003).

11.6 Conclusion

This study evaluated the potential use of the kriging method to predict the spatial variation of some surface soil properties as well as the mean annual spatial variations of atmospheric dust deposition rates and heavy metal contents in the Gavkhuni sub-basin. The spatial distribution pattern of the heavy metal showed that the deposition rate of heavy metals is greater in the western parts of the study area than the other parts. Since the spatial distributions of the atmospheric deposition rate of heavy metals in the region are similar to those of the annual deposition rates of dusts in the region, it could be concluded that the spatial distribution of heavy metals in the study area is largely affected by the deposition rate of atmospheric dusts in the region and is less dependent on the spatial distribution of the mean concentration of these heavy metals in the soil surface of the studied regions.

Furthermore, the abundance of fine sand fraction in dust samples indicates the regionality of the source of dusts in the study area. In addition, due to the similarity of the type and abundance of minerals in dusts to the minerals in the surface soil of the region, and also the closer proximity of the Ti/Zr and Si/Zr ratios, as well as the comparison of particle size distribution of dusts and the surface soil, it appears that the dust deposition in the study area has been affected by the surface soil of the region. Therefore, it can be admitted that the main origins of dust production in the study area are the surface soil of the region.

On the other hand, despite the lack of water in the Gavkhuni wetland, due to the presence of polygonal salt flats in the wetland bed and the presence of moisture in the surface sediments of the wetland, the emission of dust from its surface has not yet reached a critical stage and the wetland has not yet entered the dust production cycle. However, considering the orientation of the dominant wind direction over the year of study, a salt tsunami and its movement to the city of Isfahan is predicted if the wetland is not restored. To avoid this disaster, it is extremely necessary to apply a more sustainable water management system in the upland area which can supply enough water for the Gavkhuni wetland before it entirely dries up. Such conditions can lead to severe environmental problems (like the salinization of the agricultural lands and thus the destruction of over 100,000 ha of fertile plains in the region and, eventually desertification) and will endanger the health of locals, the city of Isfahan and even neighboring provinces, and may lead to diseases of the skin, eyes, and respiratory tract.

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Part IV
Possible Solutions for the Region

Chapter 12
Participatory Development of Strategies for the Transformation of Agriculture in the Zayandeh Rud River Basin

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12.1 Water and Land Management in the Zayandeh Rud River Basin

The integrated management of water and land resources in the Zayandeh Rud basin is facing many challenges aggravated by large fluctuations in the annual rainfall and the volume of upstream water reservoirs over the last 10–20 years. Severe droughts have led to drastic changes in surface water supply for all stakeholders in the basin, and to an unpredictable irrigation water supply for agriculture. A factor adding to problems in water availability and access is the current practice to transfer water from the Zayandeh Rud basin to neighbouring basins.

In recent years, the river has repeatedly dried up before reaching the city of Isfahan due to irregular and changing rainfall patterns compounded by growing demand for water in the entire basin, particularly in the upstream regions (Raber et al. 2017). The reservoir releases that fill the city's river bed are timed to provide water for domestic, industrial uses and, with lower priority, for the environment and irrigation (Torfe et al. 2017). The sharp reductions in the annual reservoir discharge in drought years of up to 60% compared to the wet baseline year 2005–2006 (Fig. 12.1) have forced farmers to decrease the total cultivation area in those years by almost 40%. The overuse of groundwater to compensate for the lack of surface water has caused groundwater levels to drop by 20–50 m, disrupting traditional water supply systems such as qanats and shallow wells (Mohajeri et al. 2016).

These developments contribute to the uncertainty of water availability in the basin and pose a great challenge for enterprises in sectors like farming that cannot perform properly without a foreseeable water supply. Without knowledge about the water availability for the coming season, and having little or no say in decision-making about water supply, farmers are prone to allocate their resources unfavourably (i.e. cultivated land, water and other inputs such as seed, fertilizer, and labour) and consequently suffer higher-income losses.

Resource management in the Zayandeh Rud basin needs to be aligned with the water resources carrying capacity of the basin. Balancing water consumption with the regional water budget and expected fluctuations will require a transformation of the agriculture in the basin, reducing or changing agricultural land use long term (Raber et al. 2017). Strategies need to be developed and implemented for adapting the highly seasonal agricultural water demand to the current water availability, as

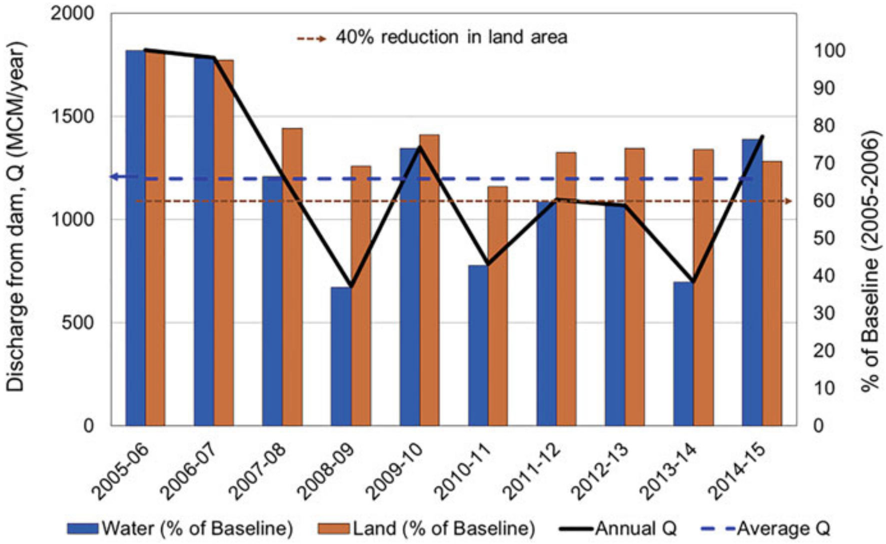

Fig. 12.1 Historical changes in water supply (blue column) and cultivated land area (brown column) compared to the baseline year 2005–2006 (source: Ministry of Agriculture Jihad 2018, Ministry of Energy 2018)

well as for aligning the overall cultivated area with the long-term projected water scarcity in the Zayandeh Rud basin (Zamani et al. 2019). The required strategies need to reconcile the multiple expectations related to technical feasibility, economic viability, ecologic soundness, and social acceptance from the diverse stakeholders.

To reach these objectives, a strongly interactive process involving multiple local stakeholders from agriculture, rural development, water resources and related fields was initiated and moderated during the project "Integrated Water Resources Management Zayandeh Rud" (start: 3/2016, end: 12/2018) in cooperation between German and Iranian project partners. The present chapter describes the participatory approaches used with local farmers, farmer organizations, water authorities, non-governmental organizations, governmental organizations and science in this process. A variety of methods and tools were adapted and applied in the project to design strategies and formulate specific measures and activities for the transformation of agriculture in the Zayandeh Rud basin. This chapter gives an overview of the participatory methods employed for strategy development and discusses the results from their application.

Table 12.1 Overview of participatory actions

Activity	Participants	Location and date
Expert workshop on agricultural measures	Agricultural and water experts	Isfahan/10 and 11th March 2015
Interviews	Local farmers in Roodasht irrigation district	Isfahan/March 2015
Citizens' jury workshop	Farmers and agricultural functionaries from up and downstream in the basin and agricultural and water experts	Isfahan/11 and 12th December 2016
Strategy development workshop	Agricultural and water experts	Isfahan/14th to 16th August 2017
Strategy validation	Agricultural and water experts	Isfahan/10th December 2018

12.2 Participatory Approach

Developing transformation strategies to adapt farming systems to water-scarcity conditions is a challenging task, as it has to consider the complexity of interdependencies between resources as well as interactions between stakeholders. Farming systems have been described as an interrelated matrix of different inputs including soil, water, plants, animals, implements, energy, labour, capital and other inputs controlled in parts by farming families and influenced to varying degrees by political, economic, institutional and social forces that operate at many levels (Doppler 2000). Expedient strategies for changes need to take the biophysical aspects (e.g. soil, water, plants, animals and energy), economic aspects (e.g. labour, capital and policies), social aspects and political aspects into consideration at both the level of the farming systems, the region and the basin (Doppler 2000). Interactions in a river basin between the economic and physical systems are complex, diverse and subject to different perceptions. The process of strategy development should include this complexity and diversity in order to create a common understanding of agricultural transformation among the stakeholders. Therefore, various actors from different sectors in the Zayandeh Rud basin were invited to participate in a series of participatory workshops listed in Table 12.1 with the aim to develop strategies for the transformation of agriculture.

The basic goals of the participatory process were to identify and prioritize measures for agricultural transformation, estimate impacts and determine preconditions of measures for agricultural transformation as well as formulate pathways for their implementation. The participants were selected according to the tools' requirements, often including a mixture of farm advisers, experts from scientific institutions, governmental bodies, NGOs, local administrations and farmers.

12.2.1 Expert Workshop

To begin the process, a 2-day expert workshop was conducted to identify general topical areas for the transformation of agriculture in the Zayandeh Rud basin. The workshop was held in collaboration with 11 experts from the water and agricultural sectors. This was the starting point of the participatory process and the basis for a Citizens' Jury workshop. The preparatory steps for elaborating the method for strategies development and preparing the participatory workshops were taken jointly with local experts, local farmers, experts and decision makers. Some basic decisions were made, including the decisions (1) to involve actors from the entire Zayandeh Rud catchment (i.e. also from Chaharmahal-va-Bakhtiari province) in the participatory process, since the transformation of agriculture would affect people from upstream and downstream parts of the river basin, and (2) to have farmers, as well as functionaries from farmers' associations, participate. Since agricultural transformation needs people with foresighted thinking as well as the willingness and commitment to pursue new activities and approaches for agricultural sector development, it was decided that "pioneer"-farmers should be the main target group (Horlemann et al. 2017).

In this first workshop, the framework and major topics for the transformation strategies were defined in close cooperation with the project partners and several feedback loops were included. The topics that were identified as the focus for the subsequent participatory actions were (1) agriculture management, (2) water distribution, (3) land management and soil fertility and (4) capacity development. These topics include technical measures such as modern irrigation systems, organizational measures related to agricultural production such as developing value chains, measures for improved inclusiveness by involving water users, economic measures such as subsidies, and institutional measures such as defining water rights.

12.2.2 Citizens' Jury Workshop

A stronger involvement of affected stakeholders in the process of defining and choosing measures is the main objective of The Citizens' Juries workshop method developed by Peter Dienel in the 1970s (Dienel 1978). It is based on the assumption that the explicit knowledge and competencies of affected stakeholders should be utilized to make political decisions that (also) affect the local level. By bringing together affected stakeholders (as local experts) and external experts, a Citizens' Jury workshop can be an expedient instrument for evaluating measures from the stakeholders' perspective and formulating recommendations on how to implement possible solutions for local problems. In the process, affected stakeholders who act as "juries" or consultants bring in their respective everyday knowledge, which is complemented by the external experts' know-how. This creates an adequate knowledge base for evaluating specific measures.

A 2-day Citizens' Jury workshop was carried out in Isfahan with 75 participants (farmers and functionaries) from upstream and downstream parts of the Zayandeh Rud basin. The participants recommended measures in the fields of (1) Greenhouses, (2) Changes in types, varieties and rotations of plants to increase value, (3) Optimization of the current irrigation system and (4) Introduction of innovative systems. The results were summarized in a Citizens' Report that was handed over to the decision makers for further consideration (Horlemann et al. 2017).

12.2.3 Strategy Development Workshop

A major requirement identified for the next step in the participatory process was the specification of the measures and their integration into consistent strategies for implementation. The project partners decided to conduct a strategy development workshop for further specifying the measures recommended in the previous Citizens' Jury and formulating strategies for implementation. In order to prioritize the measures, the workshop included an assessment of the measures in terms of their strengths, weaknesses, opportunities and threats (SWOT), as well as their preconditions and responsible actors.

The workshop was conducted in the city of Isfahan with 59 participants including entrepreneurs from the agricultural and water sectors, advisors and civil society representatives from all over the Zayandeh Rud catchment. Participants from the first expert workshop and Citizens' Jury workshop were invited to participate in the workshop in order to prevent any breaks in continuity between the workshops and maintain the common thread during the strategy development process.

The participatory actions conducted during the workshop included (1) a SWOT Analysis session, and (2) a TOWS Analysis session to generate, assess and select measures and strategies. On the basis of the TOWS Matrix, we elaborated pathways and preconditions for the implementation of the transformation strategies in the basin.

12.3 Transformation Strategies

Many strategies have been proposed by authors and organizations dealing with widely diverse farming systems throughout the world for adapting agriculture to changes in water availability (Mainuddin et al. 2010; Turral et al. 2011; Altieri et al. 2015). A review of the strategies proposed in the literature was made before initiating the participatory strategy development process. The result indicated a high consistency of potential strategies across climates and continents including: (1) Adjustments in water and soil management (water conservation and harvesting, irrigation and soil erosion control), (2) diversification of production (crop diversification, maintaining local genetic diversity and integration of animal husbandry),

(3) adjustments in agricultural production methods (soil organic management, crop calendar and greenhouses), (4) use of resistant species and varieties and stress-tolerance improvement (conservation of resistant species, selection, breeding and distribution) and (5) ecosystem protection and restoration (watershed restoration, reforestation and habitat protection) (Mijatović et al. 2013; Altieri et al. 2015). These strategies are most often proposed in conjunction with strategies that involve non-technical measures for improving organizations' capacity across systems (e.g. water user associations and cooperatives) and policy measures encouraging farmers to diversify into non-farm activities or promoting the conversion of farmland to non-agricultural purposes.

For the future development of agricultural production within the Zayandeh Rud basin that is facing continued water scarcity, expert group discussions in the IWRM Zayandeh Rud project resulted in four focus areas of transformation strategies that fall roughly within the categories above: (1) agricultural management, (2) water distribution, (3) land management and soil fertility and (4) capacity development. These focus areas were confirmed as being of high relevance in the subsequent participatory activities and strategies were developed in each area. In the following section, the main outcomes from the participatory processes in the project are presented. A more detailed description of the outcomes can be found in the final project report (Kraatz et al. 2018).

12.3.1 Agricultural Production Management

The focus of the participatory strategy development in agricultural management in the IWRM Zayandeh Rud project was on how to adapt agricultural systems to the variability in water supply. The identified strategies include:

- Choosing cropping patterns according to crop water requirement and water supply timing.
- Developing value chains based on new crops and products.
- Building and operating water-efficient medium-scale greenhouses in temperate regions.
- Establishing aquaculture ponds.

In the participatory process, the strategies were further specified with targeted impacts, measures and activities. Most of the impacts expected from the strategies centre around better planning and coordination of agricultural activities throughout the basin, and intensifying capacity development activities. This may be achieved mainly through measures for disseminating current knowledge, creating new structures and networks for the coordination of the stakeholders with the goal to improve the economic productivity of the resources water and land.

Many agricultural management strategies including greenhouses, aqua-ponds and new value chains can only be established successfully if there is a guaranteed and secure water supply. The strategies described next need to be combined with measures for improved water supply including improved governance and performance of institutions for water supply and water scarcity risk management.

12.3.1.1 Irrigation According to Crop Water Requirements

The strategies developed in the workshops focus on better management of crops and irrigation in terms of quantity and timing according to the crop water requirement, rather than on implementing new technologies. The strategies aim at positive impacts on (1) water productivity, (2) crop water demand and irrigation management and (3) ability to cope with water scarcity. The need to determine the water requirements of different crops in the basin, assess the productivity of current and alternative water uses and facilitate access to information were judged to be important factors to successfully implement the measures and achieve the impacts targeted with the strategy.

A key step to improving water productivity is to assess the status quo and then act upon it. At the core of the measures for improving water productivity is the plan to use the analysis of the historical crop water requirements to enable farmers to select appropriate crops between districts, fitting the cropping pattern to the available water supply and aligning production with the requirements of the local population for food and feed.

The proposed activities aim at generating and transferring knowledge on crops and irrigation management to stakeholders, in most cases, the farmers. A key activity is to set up an integrated service based on a knowledge database and decision support system easily accessible to farmers, e.g. via the web.

Another measure proposed was to develop a plan for better coordinating response measures to situations of variable water supply in the Zayandeh Rud basin. Other knowledge-based measures and activities centre on developing alternative land uses which have a positive effect on soil and water.

12.3.1.2 Value Chains for New Crops and Products

The strategy of developing value chains for new crops and products targets three impacts including (1) upgrading farmers' knowledge and awareness about cultivating, processing and marketing new crops and products; (2) increasing cultivation and processing of new crops and/or varieties and (3) improving the performance of value chains for new crops and products.

A precondition of this strategy is that farmers in the basin have access to information about the functions and benefits offered by new crops and varieties within the basin and are able to adopt them. This requires the farmers' participation and early involvement in the process of developing future visions for farming in the region. More specifically, enhancing their knowledge about the economic, environmental, or community benefits of new crops is crucial, in addition to getting their input on how they can be practically implemented.

Developing supply chains for new crops and products is crucial and requires the support of the government. The respective measures and activities proposed in the workshop include specific funding for the cultivation and processing of new crops. Funding opportunities are needed to raise entrepreneurial interests of the farmers for the new crops and products. The funding might be in the form of specific loans or direct financing, e.g. seeds or special machinery and technical equipment for cultivating and processing new crops and products.

Providing start-up support for the agricultural part of the process is another measure suggested by the workshop participants. The implementation of a new value chain needs a holistic approach including technical and managerial support along the whole value chain beyond the farm scale (e.g. transport, cooling, processing and retail).

12.3.1.3 Water-Efficient Greenhouses

Increasing the number of greenhouses in temperate regions of the Zayandeh Rud River Basin was proposed in the workshops as a strategy for the transformation of agriculture. The participants envisioned the construction of water-efficient medium-scale (5000–10,000 m^2) greenhouses. The challenges of developing greenhouses production systems are multifaceted ranging from high capital costs, high level of technology and management skills required for production, to developing the value chain in the case of new products including transport and processing logistics as well as marketing for delivering the products to customers. The emphasis of the three targeted impacts of this strategy is on (1) capacity building and knowledge transfer about technologies adapted to the regional conditions, (2) management and provision of financial resources and (3) supply chain for processing and marketing of the greenhouse products generate income in the basin.

12.3.2 Water Management

The climate variability and overuse of water resources in the Zayandeh Rud basin have caused severe water scarcity in agriculture, especially in the eastern part of the basin. Raber et al. (2017) identified the major issues of water management as fluctuation in water availability, lack of transparent and accepted documentation of water rights, weak enforcement of existing laws and regulations, and uncertainty about spatial and temporal water distribution in the basin. In order to address these issues, the workshop elaborated on two strategies presented in the following section.

12.3.2.1 Water Distribution

The participatory development of an adaptive water allocation procedure was proposed as a strategy to reach an agreement on water rights. The adaptive allocation procedure would take current and future water supply into account for all irrigation networks in the basin and set the basis for transparent water distribution. Such an adaptive procedure requires a profound knowledge of water availability and water allocation processes in the basin.

In addition, the collective development and adoption of a water scarcity countervailing mechanism are envisaged based on transparent rules for determining beneficiaries, quantities and timing of water distribution. This financial mechanism is proposed to safeguard sustainable income of vulnerable water users, like farmers in the downstream regions of the basin.

As a basis for water distributions negotiations, the participants called for the establishment of a database generally accepted by all stakeholders. Another measure proposed was to report and stop illegal surface and groundwater extractions as soon as possible with effective collaboration of farmers across the basin. The establishment of a "water court" was suggested to prevent illegal water extractions and enforce water laws and regulations based on sound judiciary processes.

Considering growing conflicts over water allocation between farmers and government, mediation and coordination are seen as an important strategy in the Zayandeh Rud basin. The current River Basin Organization (RBO) was proposed as the mediating and coordinating actor, although this requires empowering the RBO. In addition, a Regional Coordination Council is proposed to be established in each district or irrigation network to facilitate, coordinate, operationalize and continuously improve the implementation of transformation strategies at different levels in the Zayandeh Rud basin (see Chap. 14 for further descriptions on the role and position of River Basin Organization and Regional Coordination Councils).

12.3.2.2 Wastewater Reuse in Agriculture

Reusing urban wastewater in agriculture can partially contribute to supplying the increasing demand for irrigation water in agriculture. Enforcing regulations for wastewater treatment to meet discharge standards is needed to improve the quality of the surface water and groundwater. Water quantity may be considered as a factor in water distribution plans once the water rights are handled transparently. Indeed, improved measures to increase the quality of discharges or return water flows, in general, are needed so that cross-contamination of water resources does not take place. Training farmers to use wastewater safely is strongly recommended when reusing urban wastewater resources in agriculture.

12.3.3 Soil Fertility Management

The impacts within the strategy of soil fertility management are targeted towards soil conservation and capacity development for better soil management. An overarching measure defined within this strategy is the establishment of a soil work-group as part of the RBO and the Regional Coordination Councils to coordinate relevant institutions and actors (e.g. soil science, farmers' associations, farmers, administration and authorities) dealing with soil management. This coordination among sectors and actors should help the creation of a common soil data database, soil quality classification and zoning for land use change for reducing water demand in agriculture. Organizations involved in soil sciences research are expected to contribute by building a soil database that provides site-specific information about soil conditions. A complementary measure defined within the workshop is the continuous control of the soil qualities for assessing the impact of management measures such as reforestation using agroforestry and agro-silvo-pastoral systems. These measures are expected to contribute to reducing water evaporation and soil erosion as well as stabilizing the soil structure, increasing organic matter content, fertilizing soils organically (e.g. using legume species), avoiding overgrazing of rangelands, increasing biodiversity and even diversifying production and income sources.

Besides the improvement of the agricultural use of land, protection and restoration of natural ecosystems is an important goal in the basin (see also Raber et al. 2017). Strategic planning of resource use (e.g. water, fertilizer and pesticides) for wetland restoration or protecting groundwater resources are highlighted as important measures to improve the soil management in the basin.

An important precondition for the implementation of these measures is a change of land use throughout the basin including the reduction of agricultural land use, especially for the Roodasht region of 40% on average (Zare and Libra 2018). This would correspond to historical reductions in land area in the last decade. Besides a definite reduction in agricultural land, changes in cultivated area of some crops within the districts were suggested. The need to reduce agricultural area and adapt cropping patterns demonstrates the narrow leeway of action for adapting the region to the changing climate and site conditions. Such measures will need to be discussed in a broad circle of stakeholders in the future.

12.3.4 Capacity Development

Farmers in the Zayandeh Rud basin have been confronted with the challenge to respond flexibly to water availability in the past. The ability to manage the challenges of water scarcity and changing climate conditions will determine their existence even more in the future. Therefore, capacity development at the level of individual farmers and organizations of farmer is paramount for enhancing interaction, building trust and creating synergy between research institutions and public and private sector actors, farmers and co-operatives to enable them to carry out a wide range of necessary activities, investments and decisions towards the transformation of agriculture.

12.3.4.1 Agricultural Extension, Education and Consultation Services

Measures to transfer knowledge from research, policy and industry to farmers were prioritized by the workshop participants, as well as the sharing of knowledge between farmers.

This is in line with the measure proposed by the participants to provide modern information and communication technologies (ICT) to farmers for easier communication and sharing of information.

12.3.4.2 Agricultural Cooperatives Development

The empowerment of existing cooperatives and the promotion of new agricultural production cooperatives are considered by the workshop participants as important measures for improving market access, augmenting bargaining power, creating added value and stabilizing trade relationships with the retailers. An important precondition mentioned for these measures is financial support.

12.4 Transformation Strategies Roadmap

After identifying, validating and agreeing on the strategies, impacts, measures and activities for the transformation of agriculture in the Zayandeh Rud basin, the next step requires the selection, prioritization and coordination of the strategies. We developed a preliminary implementation plan based on the prioritizations identified in the workshops for the strategies, measures and activities. The strategy roadmap describes the logical and temporal sequence of the four focus areas (i.e. capacity development, agricultural management, water distribution, and land management and soil fertility) and strategies developed through the participatory approaches in the IWRM Zayandeh Rud project.

The resulting strategy roadmap displayed in Fig. 12.2 reiterates the importance of developing the required governance structures such as the Coordination Councils at the district and irrigation network level as well as the RBO for better coordination among the various stakeholders in the basin.

The participatory workshops described in the previous sections confirm that the transformation of agriculture in the Zayandeh Rud basin includes more than implementing technical solutions or introducing water-efficient farming practices. The transformation also includes catalyzing a paradigm shift from supply-side to demand-side water management.

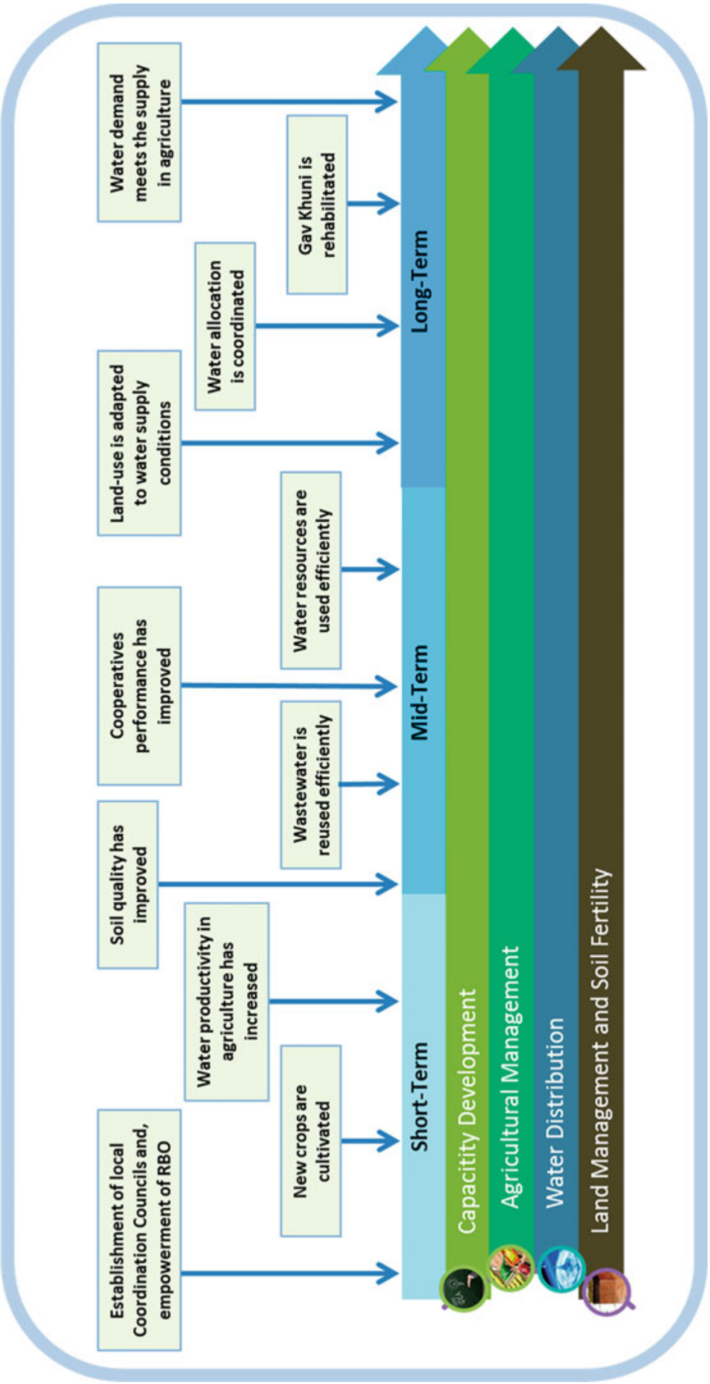

Fig. 12.2 Strategy roadmap for agricultural transformation in the Zayandeh Rud basin

A basic requirement for all strategies is the development and continuous management of a common knowledge base and a set of decision support tools for integrated resource management.

12.5 Lessons Learned and Recommendations

The development of the transformation strategies for agriculture in the Zayandeh Rud basin is an ongoing and interdisciplinary process that benefits from participatory approaches (e.g. Horlemann et al. 2017; Kraatz et al. 2018). In the previous sections, some insights were given into the application of the participatory strategy development approach and results were presented including an outlook in the strategy roadmap with recommended future activities for the implementation of IWRM in the basin.

A lesson learned from the method application is that the use of participatory methods is very context specific and results need to be reflected against the background of the specific conditions in which the methods were applied. Some challenges or limitations encountered during the application of participatory methods and tools, especially in international projects, include the time-consuming process of participatory development of strategies, additional resource requirements for language translation and organizational arrangements with local stakeholders, careful selection and effective involvement of appropriate and highly motivated participants in the beginning of project, providing financial and non-financial resources needed for implementing the participatory approaches, validating, verifying and discussing results, meeting scientific requirements, building consensus among participants in an inter- and transdisciplinary context, and taking responsibility for measures and activities by local stakeholders.

Despite the challenges and limitations encountered, the participatory development of transformation strategies revealed many advantages, particularly its potential to provide a real application and adaption of approaches and in-practice realization of research findings according to the actual needs of stakeholders. To consider the perspective and valorize contributions from weaker or affected stakeholders in problem identification and solution formulation for agricultural transformation and resource management is a relevant contribution of participatory processes. This can contribute to building trust among stakeholders and make important steps towards conflict resolution. Transformation of policy and decision making processes need sufficient political consensus and appropriate financial and non-financial resources. Involvement of multiple stakeholders for participatory transformation of agriculture may reduce transformation costs and accelerate the progress of transformations.

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Chapter 13
Environmental Capacity Building Program for the Residents of the Zayandeh Rud Basin

Khousheh Azimpour Tabrizi

Contents

13.1 Introduction

The Women's Society Against Environmental Pollution—Isfahan Branch (WSAEPisf) was founded in November 1998 as an NGO by a group of women from Isfahan, Iran, interested in the sustainable development of the environment of Iran and helping to achieve the realization of a civil society in this country. This society started its career with the guidance of the founder of the WSAEP, Dr. Mahlagha Mallah.

The founders of this society, in collaboration with other NGOs in the province, have tried to boost environmental awareness among different casts of the Province of Isfahan in central Iran. The main objective is to promote the environmental culture among different people through continuous research and education and the promotion of environmental ethics. This objective is only fulfilled if the knowledge

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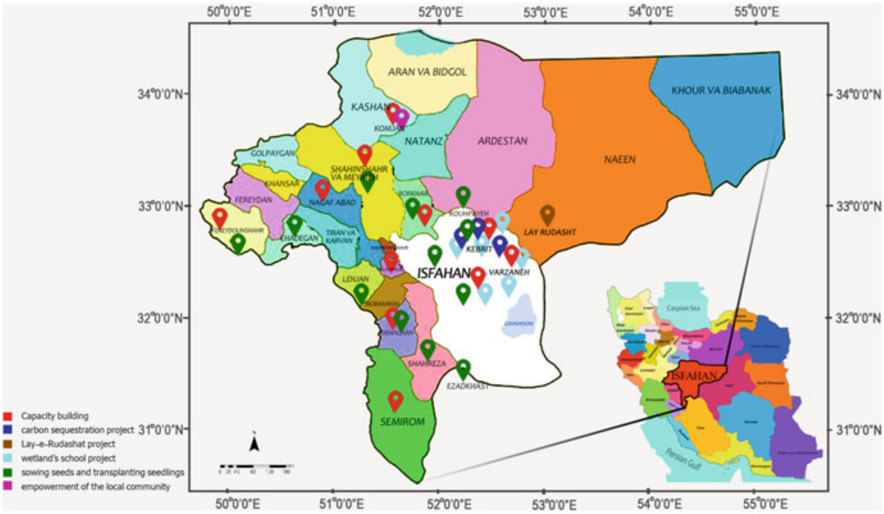

Fig. 13.1 Dispersion map of the activities of the WSAEPisf at the provincial level

obtained becomes part of people's everyday lives through which they protect the environment and their natural heritage.

The NGO also works in close cooperation with certain state departments, such as Isfahan's General Directorate of Environmental Protection, Higher Education Centers, Department of Education, Department of Natural Resources and Watershed Management, Department of Health, municipalities, and several industries of the province to provide the basis for the formation of specialized groups to solve the environmental challenges of the province.

The NGO, moreover, has been planting seeds and seedlings along the Zayandeh Rud basin in order to develop green spaces and maintain water resources sustainably. Constant monitoring and communication with the rural community of the Gavkhouni Wetland have made this NGO one of the main supporters of this wetland.

The WSAEPisf has sought to connect with domestic and international environmental activists by holding seminars, meetings, and workshops, as well as publishing posters, brochures, and educational pamphlets to realize its environmental goals. (Schneider 2001)

The campaigns "Zayandeh Rud Calls Me" and "Isfahan is Beautiful Without Plastic Bags" (No to Plastic Bags) are two of such activities.

The collaboration of four generations of male and female environmental enthusiasts has vitalized the WSAEP in combating environmental pollution over the last 20 years. The NGO has been recognized and awarded with significant awards such as the 2016 National Environmental Award in the non-governmental sector and certificates of appreciation on the World Wetlands Day (Fig. 13.1).

13.2 WSAEPisf's Areas of Operations in the Zayandeh Rud Basin

WSAEP considers the dryness of the Zayandeh Rud River and the Gavkhouni International Wetland as one of the most important environmental crises in Iran. These dried areas are not only serious threats to the province of Isfahan, but are also becoming major areas of saltmarsh and a center for haze that affects hundreds of kilometers of ecosystems in Central Iran. Therefore, the NGO has put the perpetuation and maintenance of the Zayandeh Rud River top of its list of priorities (Fig. 13.2).

Examples of activities carried out by WSAEPisf to achieve the above objectives include:

- Involvement of all social groups residing in the Rudasht Rural District to commemorate the World Wetlands Day (Feb. 2), has been held adjacent to the Gavkhouni International Wetland at local, national, and international levels.
- Cooperating in forming the campaign "Zayandeh Rud Calls Me" including a petition against the overstressing on the Zayandeh Rud River. 10,000 signatures of citizens from all over Iran were handed over to the officials.
- Holding annual photography exhibitions about the Zayandeh Rud River and the Gavkhouni Wetland.
- Holding workshops for the local community for identifying indigenous plant species under threat of extinction in the area and for taking practical steps to preserve them.

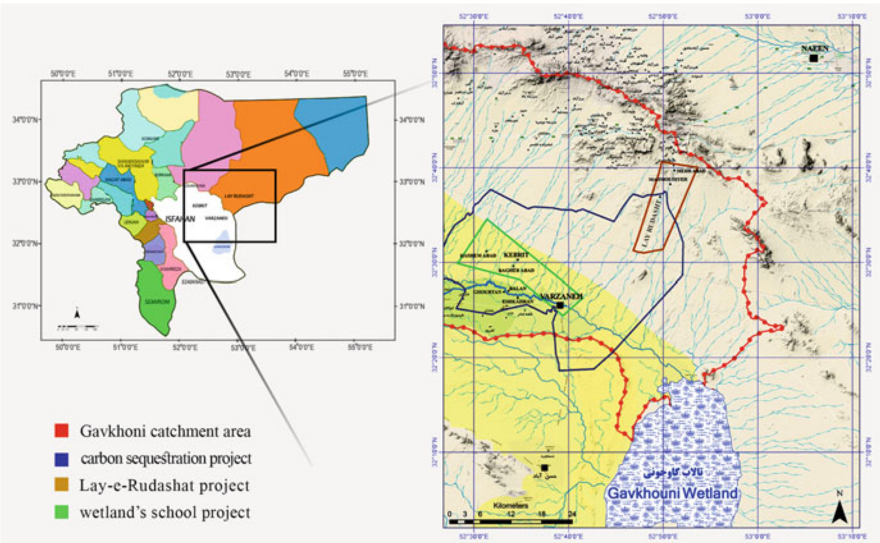

Fig. 13.2 The scope of activities of WSAEPisf in Gavkhouni Wetland Basin

- Collaborating on the carbon sequestration project and training the women in the area and establishing local cooperatives for the employment of housewives.
- Training children and families for waste separation.
- Implementing alternative livelihood programs for women in Varzaneh district and preserving local handicrafts.
- Attending wetland local schools and familiarizing children with the values and functions of the Gavkhouni International Wetland.

13.2.1 Celebration of the World Wetlands Day

Due to the importance of the Gavkhouni wetland and the attention people of this area pay to this wetland in the city of Isfahan, and the involvement of all the social groups living in the Rudasht area, International Wetlands Day (Feb. 2), is celebrated every year on February 2nd and certain programs are held simultaneously. These programs and conferences have been held at three levels of local, national, and international adjacent to the Gavkhouni international wetland.

World Wetlands Day has been held adjacent to Gavkhouni wetland by the local people and environmentalists since 2000. However, the 2016 World Wetlands Day was held in three areas in the presence of the Deputy Secretary-General of Ramsar Convention and its representatives, the United Nations Interim Administration Mission in Iran, guests from Iraq, Azerbaijan, and Australia, the Head of the Department of Environment of Iran, the heads of the General Offices of Department of Environment of provinces of Iran, the Governor of Isfahan and other authorities in the province, local authorities, NGOs, academics, students, and citizens. Moreover, on this day, the Gavkhouni Wetland Stamp was debuted, the activists of the wetland were recognized, and a special certificate of appreciation was granted to the representative of the WSAEPisf.

After the success of World Wetlands Day in 2016, the WSAEPisf asked the Secretariat of the Ramsar Convention to list the historic city of Varzaneh as the oldest wetland town. The first draft was approved and the project form for wetland cities prepared and by this Convention all the member countries around the world were notified. The documentation of the city of Varzaneh were submitted and it is now awaiting arbitration. Ms. Khousheh Azimpour is the WSAEPisf's representative appointed by the Department of Environment of Isfahan to follow on this subject.

In this regard, a campaign was started by some fans of the city of Isfahan to object to the overloading on the Zayandeh Rud River and the consequent aridity of the river. The Campaign was registered on the Change.org website as a petition. The purpose of the petition was to attract the attention of people to the dire state of the Zyandeh Rud River. The campaign was started in the city of Isfahan but soon was publicized in other cities and even some other nationals who were interested in Iran participated and signed the petition. In a very short time about 10,000 people signed the petition. The signed text was submitted to provincial and national officials (Figs. 13.3, 13.4, 13.5, and 13.6).

Fig. 13.3 The petition of "Zayandeh Rud Calls Me"

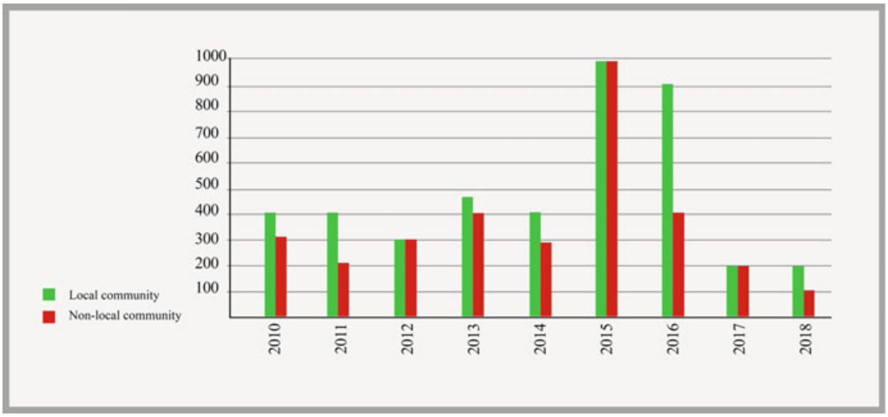

Fig. 13.4 The diagram of the participants from 2010 to 2018

13.2.2 *Participatory Revitalization of Endangered Rangeland Plant Species in the Lay Rudasht Region of Gavkhouni Wetland Basin*

This project aims at revitalizing 125 hectares of rangelands in northern Gavkhouni wetland, known as Lay Rudasht, which is one of the suppliers of Water Right for the Gavkhouni wetland. The revitalization is conducted with the use of multipurpose pasture plant species and with the involvement of local communities and beneficiaries thus to be promoted as a sample area for other local communities with similar climates.

(a)

(b)

Fig. 13.5 Holding the World Wetlands Day at National Level

The study area includes Mahmoudiyeh and Mehrabad villages 130 km east of Isfahan. The region's rangelands are among steppe rangelands with dominant vegetation of *Artemisia sieberi*, and the average rainfall of about 100 mm, which in recent years has been dramatically affected by climate change and the consequent droughts.

(a)

(b)

Fig. 13.6 Holding the World Wetlands Day at International Level with the presence of the Representative of Ramsar Convention

Table 13.1 Stages of the project "Participatory revitalization of endangered pasture plant species in the Lay Rudasht region of Gavkhouni wetland basin"

Project name: Participatory revitalization of endangered pasture plant species in the Lay Rudasht region of Gavkhouni wetland basin	
Overall goal: Participatory revitalization of endangered pasture plant species in the Lay Rudasht region	
Immediate objective: Making extra money by making side products and reducing livestock grazing on rangelands	
Problem/Issue: Destruction of multi-purpose herbaceous species in the region's rangelands	Indicators: The number of plants per unit area has decreased
Outputs 1: Promoting a culture for the protection of natural resources	
Activity 1-1: Holding workshops for men	Male participation rate at the workshops was 35 people or 70% of the total population
Activity 1-2: Holding workshops for women	Female attendance at the workshops was 25 or 85% of the total population
Outputs 2: Restoration of certain plant species	
Activity 2-1: Transplanting of seedlings in the field	The number of seedlings of species (5 species) transplanted in the field were 5000 seedlings
Activity 2-2: Sowing seeds in the field	5000 hectares
Activity 2-3: Protection of the area	Preventing the livestock from grazing the rangeland for 730 days
Outputs 3: Increasing the spirit of participation in the local community	
Activity 3-1: Planting trees in the field	Establishing a cooperative for women's handicrafts, in which 20% or 66% of the total population were involved
Activity 3-2: Establishing a cooperative for medicinal plants and the related industries	60 people or 90% of the total population of men and women

To implement the project, at first, three workshops were held with the presence of local women, men, and youths to outline the objectives of the project and exchange views with the participants, residents, and specialists regarding the selection of endangered pasture species (Table 13.1).

After holding these three workshops, the following species were selected:

- *Ferula assa-foetid*
- *Dorema ammoniacum*
- *Bonium persicum*
- *Zygophylum.spg*
- *Reum ribes*

After selection of species in springtime, and in collaboration with local trustees from Mehrabad and Mahmoudiyeh villages, a focus group began identifying the habitats and vegetation foundations and collected the relevant seeds. Considering the 2-year timeline of the pilot project, only those plants were selected that, in addition to having economic significance and consumption value, their seeds could be harvested in the shortest possible time.

After that, the seeds were planted in special pots and were kept and irrigated by local volunteers to be transferred to the rangelands at the right time. The prepared pots were transferred to the rangelands as the annual rainfalls started in autumn and were allocated 400 seedlings per hectare. Planted areas were irrigated manually once before the winter sleep. The monitoring of the species was performed at the end of the first year by all beneficiaries and community experts.

To reduce the risk of climate change and droughts, part of the harvested seeds was planted in the land vault to be transferred to the rangeland after seedlings. At the same time, other revitalization methods were used throughout the protected area, such as sow in drills, sow in pots, and sow direct.

In the second year, the operation of monitoring and re-transplanting was done. To ensure the participation of the local community and others who benefit from the activities, the following was observed:

- The plant species were selected through workshops held with the participation of local communities.
- Seed harvesting, and pot seedlings are managed by the local people.
- Representatives of the beneficiaries and farmers of Mehrabad and Mahmoudiyeh villages were present during the project implementation process.
- All transplanting of the seedlings and the seeds and irrigations and maintenance were carried out by the local community (men and women).
- Protection and preservation of the range under cultivation and non-grazing of livestock were guaranteed by local beneficiaries.

Considering the lack of an established methodology and lack of experience regarding the production of the species mentioned, there was a low probability for the germination of the seeds in the pots. However, by breaking seed dormancy, the likelihood of project's success increased.

In addition, considering the low ecological potentials in the area and low rainfall due to climate change, and the increase in the region's temperature, it was hypothesized that some seedlings and sown seeds might have stopped germinating. Therefore, to reduce the risk to a minimum, various methods of swing and different timings were considered. If necessary, re-transplanting of the seedlings and re-sowing of the seeds were planned for the following year (Figs. 13.7 and 13.8).

13.2.3 International Carbon Sequestration Project

To manage the natural resources in a participatory manner, developing the villages and to empower the villagers, the Carbon Sequestration Project (CSP) was started in 2014 in the province of Isfahan and covered about 72,000 ha of natural resources in the eastern parts of the province. The villages of Ashkahran, Bagherabad, Belan Sharifabad, Kebrit, Ghourtan, and Hashemabad with a total population of 5163 people (1460 households) were selected as pilots, and the project was run there (Mohammadi 2017). The goal of the project was to sequestrate atmospheric carbon

Project name: Participatory revitalization of endangered pasture plant species in the Lay Rudasht region of Gavkhouni wetland basin	
Overall Goal: Participatory revitalization of endangered pasture plant species in the Lay Rudasht	
Immediate Objective: Making extra money by making side products and reducing livestock grazing on rangelands	
Problem /Issue: Destruction of multi-purpose herbaceous species in the region's rangelands	Indicators :
Outputs 1: Promoting a culture for the protection of natural resources	
Activity 1 -1: Holding workshops for men	male participation rate at the workshops was 35 people or 70 percent of the total population
Activity 2-1: Holding workshops for women	female attendance at the workshops was 25 or 85% of the total population
Outputs 2: Restoration of certain plant species	
Activity 1-2 : Transplanting of seedlings in the field	number of seedlings of species (5 species) transplanted in the field were 5000 seedlings,
Activity 2-2 : Sowing seeds in the field	5000 hectares
Activity 3-2: Protection of the area	preventing the livestock from grazing the rangeland for 730 days
Outputs 3 : Increasing the spirit of participation in the local community	
Activity 1-3 : Planting trees in the field	establishing a cooperative for women's handicrafts, in which 20 or %66 of the total population were involved
Activity 2-3 : Establishing a cooperative for medicinal plants and the related industries	60 persons or %90 of the total population of men and women

Fig. 13.7 Project framework

Fig. 13.8 Activities carried out in the Lay Rudasht project

emissions by increasing plant coverage in the damaged lands, combating desertification, and improving the economic and social conditions of local communities.

This project consists of a total of six phases. Phase I: A feasibility study and the selection of a place for project implementation, Phase II: Education of the people (knowledge raising), Phase III: The establishment of the economic–social institutions (credit funds), Phase IV: Basic and participatory studies, Phase V: Establishing village development cooperatives, Phase VI: Work promotion. Sixteen months since the start of the project, phase five has now been completed.

Fig. 13.9 Location of carbon sequestration project

The most important achievements of the Carbon Sequestration Project are development of income raising activities, establishment of micro-credit funds, vocational and skill education, temporary employment loans, increased awareness, and empowerment of women. All will contribute significantly to the social and economic development of the region (Fig. 13.9).

The carbon sequestration project is for the revitalization of the damaged lands for the people (with governmental support and control), with the people (with governmental control and management) and by the people (managed by local communities) (Fig. 13.10).

The overall objectives of the project are as follows:

1. International goals: Providing an economic model for carbon sequestration and reducing greenhouse gases.
2. National goals: Preservation and restoration of damaged lands in arid and semi-arid regions with the participation of the people.
3. Regional goals: Improving human development indicators with empowerment and improvement of the economic and social conditions of people.

Implementation of this plan has resulted in the following achievements for the region:

1. Establishment of seven rural funds with 559 members (252 men and 307 women).
2. Holding training courses on mushroom cultivation, carpet weaving, sewing, etc. (45 people from each village).
3. Holding training promoting courses in the fields of environment, health, economics, and entrepreneurship (250 people) (Table 13.2).

Indicator		Average/Total	ASHKAHRAN	BAGHERABAD	BALAN	SHARIFABAD	GHOURTAN	KEBRIT	HASHEMABAD
The population	Total population	**5163**	1409	388	297	397	1242	349	1081
	Population groups	**552**	89	88	63	64	140	43	65
	Percentage Of Participation	**13.7**	6.3	22.7	21.2	16.1	11.3	12.3	6.00
The household	Whole household	**1460**	359	106	92	104	378	108	313
	Household group	**248**	35	51	25	38	45	29	25
	Percentage of participation	**26.5**	9.7	48.1	27.2	36.5	11.9	26.9	8
Women	Whole women	**2587**	689	195	145	188	635	683	552
	Women groups	**305**	49	48	38	33	68	32	37
	Percentage of participation	**15.8**	7.1	24.6	26.2	17.6	10.7	17.5	6.7
Men	Whole men	**2576**	720	193	152	209	607	166	529
	Men groups	**247**	40	40	25	31	72	11	28
	Percentage of participation	**11.6**	5.6	20.7	16.4	14.8	11.9	6.6	5.3
Groups	Total number of groups	**47**	7	7	6	6	11	4	6
	Women head	**19**	1	3	2	2	7	4	1
	Percentage of Female Leadership Participation	**40.2**	14.3	43	33.4	33.4	63.7	100	16.7

Fig. 13.10 General information for target villages up to the end of Sep. 2015

13.2.4 Wetland Local Schools

In 2015, the establishment of wetland local schools was proposed by the Focal Point of Iran to NGOs working in the field of wetlands, and the national network of wetland local schools was established on Feb 13, 2016 in Iran. The aim of the wetland local school plan is to raise students' awareness of the values and functions of the wetlands and to carry out wetland conservation activities as well as the exchange of information and achievements among marginalized students living adjacent to the wetlands. By founding the international network of wetland schools from the wetlands of Ramsar Site. Information and activities have been shared between students and they can be interconnected so as to share their different experiences more easily.

By implementing this project, the children and the general public's level of knowledge about the types of wetlands, the world of wetlands and basin areas, the values and functions of the wetlands, the importance and performance of the wetlands, the threats facing the wetlands, the social responsibility of individuals toward the wetlands, the role of humans in improving and maintaining the conditions of the wetlands, the water cycle, plant and animal biodiversity, the food chain and networks, aquatic organisms, etc. will be enhanced through the use of technology and field visits to the wetlands. From the wetland local schools, two schools were selected as samples for conducting the follow-ups. Students of these two schools will monitor the wetland's ecosystem by their periodic presence in the bank of Gavkhoni wetland and visiting Kooh-e-Siah (the Black Mountain) and observing migratory birds (Fig. 13.11).

Table 13.2 General information for target villages as of the end of Sep. 2015

The table of general information for target villages up to the end of Sep. 2015									
Indicator		Average/ Total	Ashkahran	Bagherabad	Balan	Sharifabad	Ghourtan	Kebrit	Hashemabad
The population	Total population	5163	1409	388	297	397	1242	349	1081
	Population groups	552	89	88	63	64	140	43	65
	Percentage of participation	13.7	6.3	22.7	21.2	16.1	11.3	12.3	6.00
The household	Whole household	1460	359	106	92	104	378	108	313
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Groups	Total number of groups	47	7	7	6	6	11	4	6
	Women head	19	1	3	2	2	7	4	1
	Percentage of Female Leadership Participation	40.2	14.3	43	33.4	33.4	63.7	100	16.7

Fig. 13.11 The wetlands local schools held near the Gavkhouni wetland

13.2.5 Training Children and Families for Waste Separation

After the start of the campaign "Isfahan Without Plastic Bags" by WSAEPisf, and as the authorities supported the locals with the goal of reducing the level of plastic waste in the region of Rudasht, the local population got to know the campaign well. The use of handmade cloth bags, as well as the reuse of disposable materials and the provision of functional equipment, are among the student activities in relation to the reduction of wastes at the source. Waste separation at the source, and the collection of dry waste from the rangelands around the village, is one of the promotion programs to reduce the use of plastics in this area. Of the income from the sale of solid waste collected from the participants in the project, six wheelchairs were purchased and delivered to those who needed them (Fig. 13.12).

Fig. 13.12 Waste separation

13.2.6 Implementation of Alternative Livelihood Programs and Preserving Local Handicrafts

In order to revive local handicrafts and preserve indigenous culture, which has a long history in the Rudasht region in the city of Varzaneh, the WSAEPisf decided to take an effective step in this direction. To this end, initially, workshops were held for the women of the area and they were encouraged to produce traditional handicrafts and turn them into products that could be used in modern times. In this way, these products would be publicized in the community. Among these handicrafts are traditional tablecloths with traditional folk patterns and cotton fabrics for white chadors (a kind of ancient attiring). This WSAEPisf also helped by holding tourism exhibitions and finding markets in different cities, such as Isfahan and Tehran, to create alternative livelihoods for women in the city of Varzaneh, a region afflicted with drought and aridity (Fig. 13.13).

13.3 Summary

It was such a difficult task to invite the beneficiaries to participate in the program. It was because they reside in such a region that, for many years, has been neglected by the authorities and inappropriate management has colored their lives. First, the NGO’s staff had to make the residents trust them. The NGO’s staff, therefore, stayed with them and listened to their concerns. Then, with their help and through participatory methods, they came up with practical solutions that were in line with the

Fig. 13.13 Alternative livelihoods for the regions’ women to revitalize local handicrafts

interests of the beneficiaries. Things went well from this point onwards. For example, when the residents understood well about the carbon sequestration project, things became much easier, and they all formed a well-coordinated team that did not differentiate locals from non-locals.

The programs that WSAEPisf was carrying out in the region were especially useful for children as they came to face a new world. The children of the city of Varzaneh have long been in contact with the Institute for the Intellectual Development of Children and Young Adults[1] and they have experienced indirect education, but in other villages, such as Kebrit, Bagherabad, and Hashemabad, the participatory methods were new and therefore interesting for children.

The other groups that took most of the programs were women because WSAEPisf's main focus was on the involvement of women and the creation of alternative livelihoods for them. The NGO helped the women to develop their self-esteem as they found alternative income and could support the household.

One of the particularly successful projects was the "Revitalization of Lay Rudasht's Plant Species" project. The reasons for the success of this project were:

- Family relationships among the locals of the villages involved in the program.
- The elders of the families cooperated particularly well with the NGO staff implementing the program.
- Completing all stages with the help and opinions of the stakeholders (selecting the type of seed to be supported, seeds collection, choosing reproduction methods, etc.)
- The presence of women, men, and children in all stages of the work.

The success of the project greatly depends on the beneficiaries of the region. If they continue to cooperate, and if the community vigorously follows the project to the end, the empowerment project can be regarded as having been effective. Achieving the goals at the right time and ensuring continuous monitoring of achievements by the local community ensure the sustainability of the results of the project.

WSAEPisf aims at further engaging the provincial authorities as, compared to the local authorities, they are in higher levels and therefore the NGO seeks to encourage them to pass certain laws to facilitate community and rural life. Further research is proposed to create a permanent place for the education of the local children and women. What needs to be taught in this ongoing training center requires more research and study, part of which should be shouldered by the local community.

[1]An Iranian institution with a wide range of cultural and artistic activities in the field of mental and cultural development for children and young adults (see https://en.wikipedia.org/wiki/Institute_for_the_Intellectual_Development_of_Children_and_Young_Adults).

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Chapter 14
Adaptive Land and Water Management: A Regional Action Plan for Roodasht to Cope with Climate Change

Wolf Raber and Mohammad Naser Reyhani

Contents

14.1 Introduction and Background

Sustainable water and land use management in the Zayandeh Rud basin are challenged by climate change, population growth, and unfavorable socioeconomic conditions (Gohari et al. 2013; Torfe et al. 2017; Salemi and Murray-Rust 2002).

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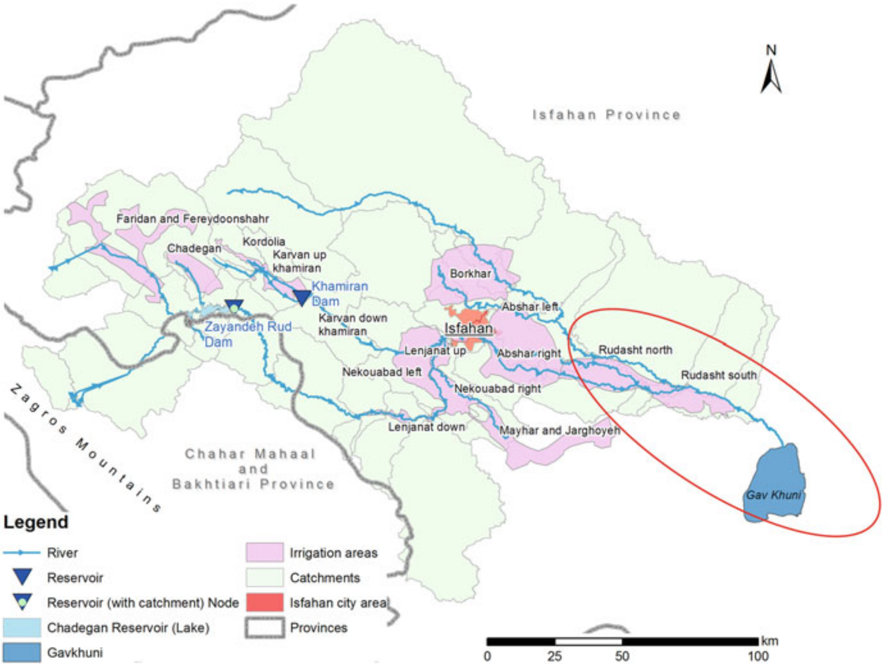

Fig. 14.1 Location of the Roodasht project area (red circle) (modified from Mohajeri et al. 2017)

In the closed basin, where every drop of water is used multiple times, the basin-wide problems are magnified in the agricultural areas at the tail end of the river course (Molle and Mamanpoush 2012).

In the period from 2015 to 2017, adaptation strategies were developed in a participatory process for these challenges. The project targeted the Roodasht region[1] downstream of the Zayandeh Rud and in the very east of the catchment (see Fig. 14.1). It was funded by the German Federal Ministry of the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) in collaboration with the German development agency GIZ, as part of the International Climate Initiative.

A vulnerability analysis of farmers in the project area was the basis for a shared and common problem understanding of the relevant sectors, describing the need to adapt to the outcomes of climatic and socioeconomic and environmental change. A multidimensional vulnerability framework (Füssel 2007), identified little and uncertain water availability, poor agricultural production, limited nonagricultural job opportunities, and the degradation of the environment and soils lead inexorably toward desertification. These factors have all been further identified as tangible threats for around 12,000 poverty prone households in Roodasht mainly occupied

[1]The Roodasht region encompasses the cultivated and populated area within the Roodasht irrigation network up to and including the Gavkhuni wetland.

with farming. For the profound analysis, research methods like expert interviews and workshops, farmer interviews according to the Grounded Theory (Glaser and Strauss 1967), fieldwork and remote sensing analysis as well as excessive studies of governmental data (regional water and agricultural authorities) have been applied.

Based on the common problem definition a multistage design was applied through a participatory process with 21 representatives of the sectors for water, agriculture, environment, the Governor's office and civil society from basin, provincial as well as local scales in the course of 1 year. The goal was to discuss and negotiate potential measures and strategies to respond to the shared problem definition.

For the process, a participatory approach has been chosen based on the Harvard Negotiation Project (Fisher et al. 2000). This approach is divided into four stages: (1) creation of a common problem perception, (2) discussion of possible methods of problem resolution, (3) selection of feasible problem resolution methods, and (4) sketching of an action plan and validating packages of measures with participants and external experts. Central aspects of this approach are a mutual recognition of all participants as conflict partners and a continuously appreciative communication structure. The Harvard principle implicates the aim of reaching an acceptable solution for all conflict partners as this is understood as the only way to guarantee a sustainable outcome (Fisher et al. 2000; Lens 2004).

The main product, a trans- and interdisciplinary developed action plan, is a central strategic tool to adapt land and water management in the region to changing climatic and socioeconomic conditions (Ribarova et al. 2011). It offers policy and decision makers practical advice for transformative management with the goal of safeguarding sustainable incomes for farmers' households under water scarce conditions, countering social conflict, and at the same time preventing desertification and environmental degradation downstream of the Zayandeh Rud.

In this chapter, an overview of the developed measures of the action plan is given. They are structured in: reconciling water distribution at basin level, agricultural management, regional management, and protection of the Gavkhuni wetland (compare Fig. 14.2).

14.2 Reconciling Water Distribution

The suggested interventions in reconciling water distribution aim to increase the reliability of water availability in the Roodasht region. Currently, local investment and efforts are hindered by planning insecurity and decreasing local water availability, a historically grown complexity of water entitlements. The main source of conflict and insecurity of stakeholders in Roodasht and the rest of the basin originates from a lack of documented volumes or reliable shares in the water entitlements as well as political decisions that do not reflect legally established water distribution rules. In order to enter a fair and legal, firm transformation process, important parts of the water distribution system need to be renegotiated, and agreements need to be

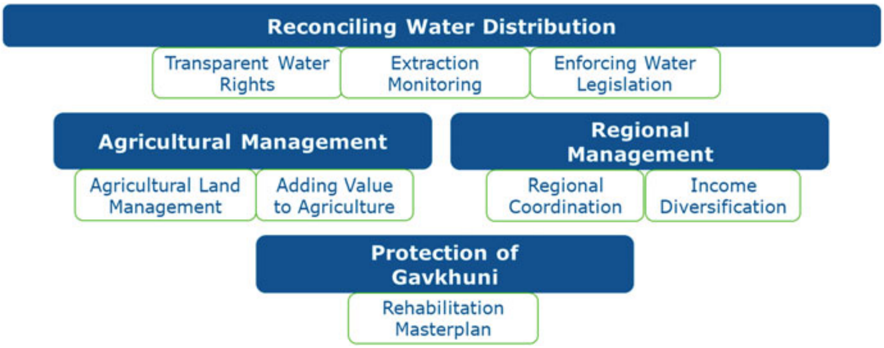

Fig. 14.2 Overview of packages of measures of the action plan for Roodasht (source: Action Plan 2019)

legally enforced. To clarify the importance of water laws and law-abidingness, for example, decisions of the Supreme Council of Water and the River Basin Organization (RBO) Zayandeh Rud, must be legally defended and equitably implemented. A lack of understanding among decision makers creates a general mistrust in the population and makes it difficult to create a stable transformation process.

In a development perspective of 20 years, the following fields of action have been brought forward in the action plan by the involved stakeholders as necessary and achievable.

14.2.1 Transparent Water Rights

Higher transparency in water distribution and institutions is identified as a crucial factor to enable a successful adaptation process in the region. The strategy stipulates that within the coming 2 years, the River Basin Organization (RBO) coordinates a process, where all forms of existing water rights are translated in a generally accepted procedure (formula) for annual calculation of water quantities distributed to individual irrigation sub-networks (Village/Sahra Level) and the Gavkhuni wetland. Transparency and ability to respond to fluctuating and decreasing water availability are essential core features for such a technocratic water allocation system. To safeguard sustainable development, normal and minimum water requirements for desertification control and stabilizing the Gavkhuni wetland need to be quantified and included in the basin-wide negotiation process. The action plan highlights that the development process of the procedure needs to involve all affected stakeholders and is flanked by a large-scale awareness raising campaign. Its results need to be made available to the public and both the people affected, as well as the institutions responsible for implementing the changes, should receive the training required for the reorganized water allocation system.

Besides the medium-term need to bring a transparent distribution mechanism for water resources into practice, for the time being, the provision of a minimum volume of water will presumably not be possible by natural means (Zayandeh Rud catchment) in water scarce years. A major reason is the severe drop of groundwater levels in the catchment upstream of Roodasht, which makes large volumes released at the central dam for the tail end, seep away in the course of the river. For this reason, a supplemental measure might be to discharge treated wastewater of the wastewater treatment plants Isfahan south and east, into the river. According to Iranian standards, the treated wastewater from these sewage plants may be conveyed through the river and can be used as an "emergency supply" to prevent desertification and for supplying the required water to the Gavkhuni wetland. The process may be facilitated by the Agricultural Trade union. It is assumed that by a stepwise normalization of groundwater levels the necessity of such "emergency supply" will be reduced in a natural way.

A further suggested pillar of action to cope with insufficient water availability to supply all water users in the basin and particularly Roodasht, is to reduce the number of water users/entitlement. It is suggested that the government consider the possibility of rebuying water rights or land with associated water rights of, for example, uneconomical agricultural areas with low soil quality in times of overall decreasing water availability. A governmental repurchase program for water rights would require implementing a compensation fund as well as transparent rules and procedures that avoid uncontrolled selling of lands and migration by farmers. Another strategy for coping with excessive water rights in the basin may be a reduction of water withdrawal permissions (different types of water entitlements than water rights) to meet the capacity of groundwater and surface water resources.

In the face of regional water shortages, the revision of compensation payments and insurance models that spring into action when water users do not receive their water shares are also considered important. In order to strengthen and augment agricultural processing industries in the Roodasht region, the possibility of financial compensation for these industries in the case of drought-related agricultural losses should be considered.

In the next paragraphs, pragmatic multipurpose agricultural measures are suggested that go in line with a regional paradigm shift from "self-sufficiency of agricultural production" to "sustainable and resource conserving agriculture and land use." Gradually aligning water supply and the water demand in agriculture as well as flanking support programs is a central task for a transformation toward sustainable and conservational agriculture in Roodasht and the basin.

14.2.2 Extraction Monitoring

To better address the issue of water scarcity in the basin, guaranteeing precise and statutory water distribution between the water users by monitoring water extractions is very important.

Necessary technologies for an area-wide measurement and monitoring system have been available on the market for years. They have been sufficiently tested and are fully operational. The focus is now on raising the willingness and financial means for choosing and installing the adequate monitoring system. In terms of fairness and transparency, all ground and surface water extraction points need to be identified and equipped with adequate measurement devices. The monitoring system must be able to gather relevant data and promptly send them to a central monitoring station or agency. The most important data on extractions and available water resources should be structured in a comprehensible way and put online for the general public. The RBO should be the central monitoring agency. The entire monitoring system should be built in a way that the data gathered are acceptable to all parties/stakeholders. This requires involving all relevant stakeholders in the planning and decision-making process.

14.2.3 Enforcing Water Legislation

The measures described can only come into effect if their implementation is observed and any disregard punished more consistently. This applies to the partly uncontrolled groundwater as well as surface water extractions. Therefore, all illegal water extractions in the catchment have to be identified and stopped as soon as possible, prior to or during the implementation of the monitoring system. Only then can a feeling of fairness be created and sustainable water resources management be realized.

The closing of illegal wells, in particular, will be a big challenge and can only be successful if all relevant authorities have committed and well-trained personnel in their legal departments, at their disposal.

In order to enhance the accountability of institutions in implementing water rights, a “Water Court” should be established that deals exclusively with water lawsuits. In addition to this court, an independent “Water Dispute Resolution Council” would have the function of solving water issues before they are brought to court. Only if the chances of success are low should disputes be brought to court. It is important to strengthen the awareness of authorities and institutions that the immediate enforcement of judicial decrees is one of their core responsibilities. Non-compliance of judicial decrees should, therefore, result in considerable punishment of the respective institution or person.

14.3 Improve Agricultural Management

The findings of the vulnerability analysis of farmers in Roodasht showed that regional agricultural land use management has not been adapted nor is it flexible enough to cope with the challenges over the past years in regard to climate

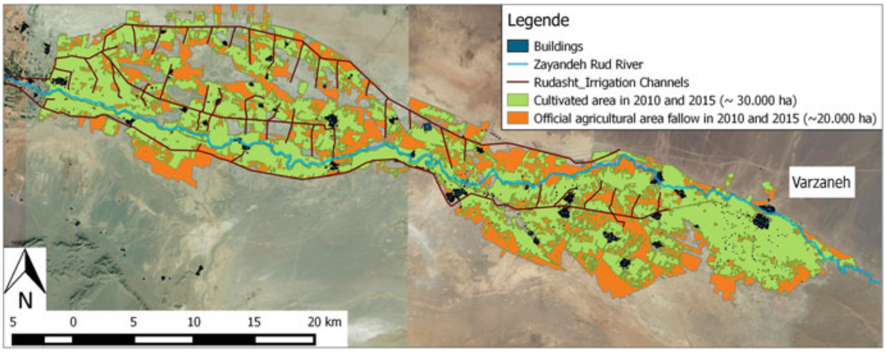

Fig. 14.3 Official agricultural area in Roodasht with patches cultivated and fallow during the past decade (satellite analysis) (source: Action Plan 2019)

variabilities, water stress, environmental degradation, and market dynamics. Therefore, the action plan addresses a range of measures for improved agricultural land management such as new zoning of land use, an improved portfolio of agricultural products, and enhancements in agricultural practices. Furthermore, approaches for adding value to agriculture by measures of establishing local value chains, empowering agricultural cooperatives, and improving regional marketing are suggested.

14.3.1 New Forms of Land Use Zoning

In order to enable a sustainable improvement of agricultural land management in the area, while respecting changes in framing conditions, identifying and establishing appropriate land use zones for agricultural-, conservational-, and commercial activities is recommended.

Figure 14.3 presents the official agricultural area of Roodasht in green and orange. However, satellite analysis reaching back to the year 2009 shows that in the past decade, with limited water supply[2] to Roodasht, only the green areas have been cultivated at least in one of the years. These areas account for 60% of the total area officially designated for agriculture. Consequently, the green areas are considered as “core” cultivated areas in the past decade. In contrast, the areas in the figure colored in orange lay fallow during these years. Large parts of the fallow areas, and in particular the ones in the border region to the desert, maybe considered degraded, lost for farmers, and in the process of desertification, as seen in site visits and according to farmers and expert interviews.

[2]In 2009, 2011, and 2014 no surface water was supplied to Roodasht, and in 2010 and 2013 water supply was significantly reduced compared to normal volumes.

Table 14.1 Proposed agricultural land use types

Land use type	Potential location	Main activities
Core cultivated area	Areas that have been cultivated in the past decade	Commercial agricultural production of field crops Livestock breeding
Conservational area	Land left fallow in the past decade	Desertification control, conservational biomass/fodder production with perennial crops and agroforestry systems, particularly in the border regions to the desert Livestock breeding in areas surrounded by cultivated area (central location)
Specialized pockets	Cultivated and fallow land close to villages	Greenhouses, orchards, permaculture, livestock breeding, processing and logistic facilities, renewable energy production (e.g., PV), and semi-central composting facilities

Source: Action Plan (2019)

In compliance with the observed development of cultivated areas in the past decade, environmental conservation and economic development, in the action plan recommendation it was agreed upon to convert the current official single "agricultural area" land use type in Roodasht into three new agricultural land use types (Table 14.1).

The specific outlines of these new agricultural land use types should be established and formalized in a participatory process with the farmers in each of the approximately 40 village/Sahra regions of the irrigation scheme. Landowners of designated conservational areas with reduced agricultural productivity and a focus on conservational activities, may either be compensated with subsidies, forms of public–private land ownership and management, tax benefits, or similar mechanisms. In a broad capacity building campaign, farmers as well as representatives of relevant institutions need to be informed on rights and obligations in regard to new agricultural land use types and compensation mechanisms.

14.3.2 Alternative Agricultural Products

Striving for sustainable economic and environmental development requires reconsidering the current agricultural strategy, which on the one hand has led to gradual soil degradation. On the other hand, it has shown limited regional added value due to little product diversity and sale of planted grains as main crops to other regions with guaranteed, but small income for farmers.

Under consideration of the local climate, scarce water resources, saline, and alkaline soils with poor soil structure and humus content, as well as apparent agricultural practices of farmers, various types of alternative crops have been developed with agricultural experts for the above-introduced land use zones.

The presented multipurpose agricultural products in Table 14.2 are quite salt and drought tolerant, prevent desertification, have benefits for the soil, may generate higher incomes for farmers and offer more options for commodity chains in the region than the currently dominant grains (wheat and barley). The afforestation of degraded cropland is an adapted land-use strategy to reduce wind erosion and ongoing desertification. Perennial shrubs and trees produce fodder and biomass for mulching of agricultural soils and may even earn carbon units for marketing in emissions trading systems.

Nevertheless, it is not wise to eradicate existing winter grains in the short term, which are well adapted to water supply patterns and comply with the historical background and empirical knowledge of farmers. On the contrary, it is suggested to facilitate a gradual medium-term diversification in crop patterns to more multipurpose crops along with the evolution of water supply patterns. In general, large crop diversity is desirable for building up resilience to climate, economic, and social change as well as pests.

The regional core products and crop types are supposed to be initiated by scientists and decision makers, but have to be finally decided on by "trial and error" on the part of farmers and entrepreneurs themselves. Public institutions can only create the framing environment and support of know-how and funds. The stepwise shift of cropping patterns needs to be oriented toward future water availability, market conditions, and success of other adaptation measures. Nevertheless, the cultivation of crops with high water demand like rice, cotton, and potato should not be encouraged by authorities. To avoid further degradation by uncontrolled grazing of livestock, Rangeland Management Plans are suggested to be set up to avoid overgrazing of livestock.

Once the changes in land use and crop patterns (in particular main areas for desertification control) are sketched and agreed upon, the central water supply infrastructure and, if necessary, the timing of irrigation water supply, should be adapted accordingly. Due to the ongoing salinization of groundwater, it is of the utmost importance that the common practice of conjunctive use of groundwater with delivered surface water is considered in the infrastructure revision. It should be examined if at certain locations (in particular for Green House Settlements) semi-central or decentralized desalinization facilities may be implemented. Furthermore, on-farm rainwater harvesting and erosion control should be applied as supplementary to reduce the irrigation water demand of plants.

14.3.3 Revising Agricultural Practice

Local soil conditions are, next to water availability, the most important factor for sustainable agricultural productivity. Data availability on soil quality in the region is poor and should be improved urgently. Anyhow, it could be found that soil in the region has good agricultural potential with high clay and silt content but with extremely low humus content, and salinity as well as alkalinity problems. On fallow

Table 14.2 Selection of proposed adapted agricultural products

Goal	Core products	Cultivation zone	Crop types (example)[a]
Production of salt- and drought-tolerant crops that may be processed to high-value products	Oil seeds	Core cultivated area	Sesame Safflower *Kochia* (*scoparia* (L) Schard)
	Medicinal products and herbs	Core cultivated area	Caraway *Rosmarinus officinalis* *Thymus vulgaris* *Silybum marianum*
		Productive rangelands	*Matricaria chamomilla* *Foeniculum vulgare* *Lavandula stoechas* Bios Salvia Reuterana Liquorice *Dorema ammoniacum* *Artimisia herba alba*
Production of high-value foods to be processed or marketed regionally or nationally	High-value food	Core cultivated area	Saffron
		Productive rangelands	Barberry Pomegranate
		Green houses	Tomato/ Paprika other vegetables
	Livestock products	Rangelands (not in border areas)	Sheep Camel Ostrich Pigeons Bees
Production of forage, conservation of degraded areas (desertification control) andbiomass production for soil improvement	Fodder / Forage	Core cultivated area	Alfalfa *Sorghum* Millet
		Productive rangelands	*Seidlitzia rosmarinus* *Kochia* (*scoparia* (L) Schard) *Aellenia subaphylla* *Nitraria*

(continued)

Table 14.2 (continued)

Goal	Core products	Cultivation zone	Crop types (example)[a]
			schoberi Cactus Agroforestry/Trees: *Prosopis* (*cineraria*) *Acacia albida* *Faidherbia albida* *Haloxylon persicum*

Source: Action Plan (2019)

[a]The capability to plant the suggested crops in Roodasht needs to be assessed in detail by local agronomic experts. Feasibility to climate, soil conditions, irrigation demand, and timing needs to be evaluated

lands, wind erosion is becoming an issue. Concrete agricultural practices suggested for improving soil quality and productivity include:

– Mulching of agricultural soils with organic material from plant residuals and compost, leaf litter, and fresh pruning from coppicing trees and shrubs cultivated in conservational areas in order to conserve soil moisture, improve soil fertility, and stimulate humus buildup through decomposition.
– Applying organic fertilizer instead of mineral fertilizer may improve soil fertility and physical structure in the long run and stimulate humus buildup.
– Planting legume crops and shrubs in order to enhance nutrient availability in the soil and improve soil structure and the microbiological regime to favor humus creation.
– Practicing intercropping or crop rotation and striving for permanent crop cover in order to conserve soil moisture, improve soil fertility, maximize production per hectare, and avoid wind erosion.
– Avoiding soil disturbance from intensive plowing by applying minimum tillage (chisel plow) to allow salts to slowly leach as well as avoiding oxidization and losing organic matter.

The action plan also highlights that capacity development of farmers, as well as relevant representatives of different institutions, is the key component for agricultural transformation. The facilitation of peer-to-peer training from farmers to farmers is identified as a powerful way to spread new information and know-how while obviating the farmers' mistrust in the administration. Involving willing farmers in research, experimental setups, and evaluation of new cultivations and land management methods, will ground research to real field conditions and empower farmers to spread firsthand information. Agricultural Service Centers and local technical consultancies need to be equipped with adequate resources to support local capacity development and training missions.

14.3.4 Improving Local Value Chains

In the area of Roodasht, about 13 processing facilities were identified which mainly process dairy products or pack vegetables. This practice creates employment for farmers and their households and effectively increases the incomes of households.

The action plan suggests expanding processing and storage facilities for (new) agricultural products. Installing and operating processing facilities are typical activities of agricultural production cooperatives or village development groups. Experience shows that in such groups, local farmers, and entrepreneurs are able to pool their resources, to efficiently manage machinery and farm inputs. Also, cooperative processing and marketing of bulk products are considered a promising strategy.

To facilitate installation of new processing facilities, granting subsidized loans, capacity building on technical skills and entrepreneurship, and allowing land use changes from agricultural land to small-scale processing facilities is suggested. Electricity and drinking water supply infrastructure should be improved particularly in the new specialized pockets close to villages where processing industry and greenhouses may be developed. In terms of logistics for farm inputs and products, the region should be equipped with a sufficient road network and potentially a dry port, where goods can be stored and shipped in bulk to Isfahan or other trade centers.

14.3.5 Empowerment of Agricultural Cooperatives

All stakeholders and experts involved in the project agreed that reinforcement of the agricultural utilization system is necessary so that small-scale farmers may cope better with uncertainties and fluctuating markets. This would involve facilitating and strengthening the current agricultural production cooperatives as has been identified, allowing the land to be worked cooperatively, reducing risks, and production costs as well as adding value.

However, despite the formal establishment of these institutions, the majority of existing cooperative companies in the region face several challenges. These are inefficient cooperative management structures, a lack of skilled human resources, and poor collaboration of the farmers due to social distrust and conflicts.

Thus, as an adaptive measure, capacity development on cooperative entrepreneurship and management is suggested. This would include professional training for managers and members of cooperatives to create a better understanding of their rights and obligations, the possibilities, functions, and benefits of such organizations. A professional training curriculum could either be facilitated by a newly established professional training center, e.g., in Isfahan or by an institution that already exists.

Furthermore, governmentally financed and facilitated Farmer-to-Farmer training by successful cooperative members from Roodasht or other parts of the country is considered a promising way to empower cooperatives and avoiding a tensed top-down interaction of governmental institutions. Another important measure is awareness raising among the farmers to encourage them to actively get involved in cooperative actions.

14.3.6 Developing Regional Marketing

It could be found that marketing of new as well as traditional products from Roodasht is currently poor. Farmers need to cope with strongly fluctuating prices, high transaction costs, and limited control and choice in selling their products. In order to improve the marketing of traditional products and pave the way for new products, a regional marketing agency could be established. In accordance with the product types and targeted customers, marketing strategies with development of a brand/label for products from Roodasht and partnering regions are realistic possibilities. Tasks of the agency could encompass a survey on regional, national, and international demands for agro-industrial products (e.g., as seed oils, and cosmetic production resources) and consumer end-products (e.g., medicinal products, vegetables and livestock products, and handicrafts).

Harnessing market potentials for new agricultural products may also influence and inspire farmers in their choice for medium-term adaptation of their crops.

14.4 Establishing Regional Management

Aside from political and legal actions, most of the recommended adaptive measures of the action plan need to be concretized for implementation in the region. But existing institutions at county and district levels are not able to thoroughly address local challenges by adaptation of the suggested measures. Therefore, a new regional institution is suggested to be established for Roodasht with the aims of organizing and developing existing human and natural resources in a way that main regional challenges can be addressed.

14.4.1 Regional Coordination Council as New Regional Institution

Establishing a regional coordinating council may coordinate, implement, as well as continuously develop and monitor the measures suggested in the action plan. It could link and coordinate locally affected people, cooperatives, informal institutions, and NGOs with decision makers from local, provincial, and river basin levels.

A type of regional management is suggested that embodies the necessary rights and duties as well as attains financial support, e.g., provided by the River Basin Organization and Isfahan's County Governor. Expertise and discretionary authority are required to assure the implementation of procedures and measures determined in the action plan. A clear, written description of the duties as well as instructions for administrations and organizations that have to collaborate with the management and implement the action plan is vital.

Furthermore, five subordinated working groups on the topics: water and soil, cooperatives, Gavkhuni wetland, regional economy, and engagement and public relations are suggested. Every institution and individual relevant for the implementation of the action plan should be represented in the working groups. The key members of this coordination council should be local experts and representatives of affected stakeholders in Roodasht. External members should be official representatives of organizations/institutions assigned for the implementation of the corresponding segments of the action plan. Furthermore, if necessary, the working groups should receive professional training on team building, conflict resolution, and project management.

The tasks of the working groups include (1) describing and evaluating the status-quo, existing regional plans, and envisioned transformation strategies; (2) concretizing and adapting measures of the action plan; (3) following up and coordinating the implementation of measures; (4) managing funds; (5) developing capacities; (6) managing local data (including climate and weather data) and providing/ analyzing key figures; as well as (7) public relations. The regional coordination council is responsible for merging the results of the working groups into a general regional vision, necessary political lobbying as well as the cross-sectoral integration and implementation of strategies.

Engagement and Public Relations are crucial tasks of the coordination council. Public relations are necessary to communicate positive developments and activities in Roodasht, but also to identify demands to relevant decision makers on provincial, river basin, or national level. On the other hand, information and events should inform people about current developments and motivate and empower citizens to participate in activities.

14.4.2 Diversify Local Income Options

Currently, raw agricultural products are the main source of income of households in the Roodasht region. To decrease reliance on agricultural products directly dependent on water supply and to increase overall household earnings, a stepwise income diversification strategy is suggested for the region. Diversification can be achieved through the establishment of new processing and commodity chains, preferably in cooperatives as discussed above. Furthermore, it is also recommended to develop income options that are not directly connected to agriculture. To this end measures like creating new services as new business segments are suggested.

Possible service segments in Roodasht are for example tourism, which includes the creation of leisure time or educational facilities, therapeutic services, holiday or gastronomic offerings within farms or natural and historic sites. Also, household handicrafts could be enhanced through capacity development in the field of handicrafts (weaving, tailoring, etc.) and entrepreneurship. New sources of income that prioritize women should be established.

14.5 Protection of Gavkhuni Wetland

Sustainable development in the Roodasht region is only possible if the Gavkhuni Wetland is restored and rehabilitated in the medium term. Only a flourishing Gavkhuni can provide its full natural ecosystem services and can, for example, hinder the dispersal of pollutants through winds. Therefore, it is important to bring the economic value of its ecosystem services into the focus of policy decisions and to develop and apply appropriate management and restoration mechanisms to regain and protect the physical, chemical, and biological integrity of the Gavkhuni wetland's ecosystem. But ecological data on the conditions and potential of the ecosystem protected by the Ramsar Conventions are scarce. The Environmental Protection Agency is supervising several ongoing studies on wetlands such as "Development of management plan for international Gavkhuni catchment." It is imperative that these studies are completed and promoted with the participation of all relevant stakeholders in the near future to draft a master plan for wetland rehabilitation.

To achieve a stepwise improvement of the wetland, a 20-year management plan, including 5-year action plans with, for example, measures for improving water quality, restoration measures, vegetation management, or ecotourism are suggested to be developed in cooperation with well-experienced international organizations and local environmental NGOs.

Involvement of local government units and nongovernmental organizations and actors in Roodasht in conservation of the Zayandeh Rud river and Gavkhuni wetland should be encouraged by institutional capacity building and public awareness raising. To keep the management and action plans up and running, a coordinating organization is suggested. Therefore, existing institutional foundations should be considered and the main elements should be integrated into the present management structure to ensure complementarity. This organization should ask for progress reports, regularly get the stakeholders and institutions together to discuss the action plan's implementation, monitor results, and decide on modifications where necessary.

14.6 Conclusions

The conducted trans- and interdisciplinary participatory approach following the Harvard Negotiations Principle (Fisher et al. 2000) could be successfully applied to perceiving the myriad of shared problems and creating a clear vision for the steps that need to be taken. The action plan is the central product of the process, comprising agreed upon strategies for water and land management, economic development, regional coordination, and environmental conservation to cope with and adapt to ongoing and further expected impacts of climate and socioeconomic change in the region.

All people and institutions involved in the preparation of this action plan consider the selected measures and strategies capable of significantly improving the socio-economic situation in Roodasht, allowing optimized use of natural resources and enhancing the flexibility and robustness of the water system to cope with uncertainties. At the same time, it is clear that the action plan is only a starting point and continuously evaluating the functionality of implemented measures and strategies has a key role for adaptation of measures. Some of the suggested approaches have already been followed up for implementation, however, apparently the implementation of those measures is neither well-coordinated nor structured and does not have the necessary speed. The main reason for this is seen in the lack of sufficient financial resources and political will for the implementation.

An overview on sequences and preconditions for implementing the proposed measures and strategies of the action plan is presented in the form of a road map in Fig. 14.4. The figure presents the order in which the fulfillment of key milestones of each proposed measure (black) are envisioned and when important development goals should be reached (green).

In this sense, the first important development goal in the Road Map is to provide a "minimum amount of water for Roodasht and Gavkhuni Wetland." To this end, a number of measures must be successfully implemented at the catchment level and in Roodasht. At first, the mathematical formula for water distribution patterns needs to be determined. Then, besides installing an extraction monitoring system, establishing a water court and stopping illegal water withdrawals, the agricultural land uses must be zoned in a participatory manner. The successful accomplishments and steps taken to this point provide the required foundation to guarantee a minimum water supply for the Gavkhuni wetland and decelerate desertification in Roodasht.

The implementation of all regional measures in the action plan would benefit from the establishment of a Regional Coordination Council as a first measure. This institution would coordinate, operationalize, and continuously improve the quality and execution of the action plan.

The second development goal in the Road Map is the creation of sustainable household incomes for farmers in Roodasht. This can be achieved by measures for agricultural and regional management including modifying agricultural production patterns, establishing a regional marketing agency, adapting agricultural practices, empowering agricultural cooperatives, installing value chains, adapting

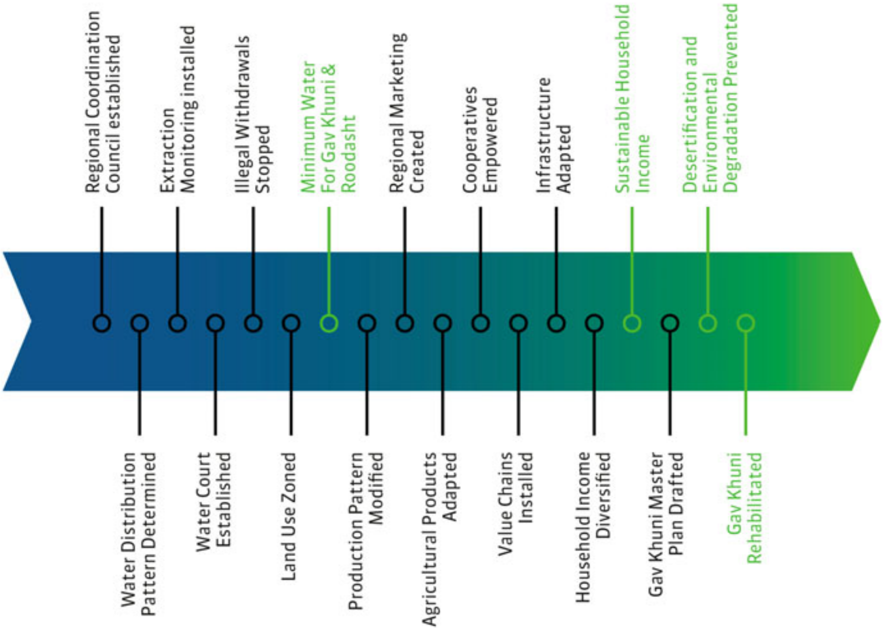

Fig. 14.4 Road Map with key milestones of the action plan (source: Action Plan 2019)

infrastructure, and finally diversifying household incomes. These measures would, in the long run, also prevent desertification and environmental degradation to a reasonable degree.

In order to rehabilitate the Gavkhuni wetland, as is proposed above, complementary studies should be carried out to draft a comprehensive master plan for the wetland's rehabilitation. With such a plan, coordinated and politically accepted steps could be taken to rehabilitate the wetland in the project's 20-year outlook. These measures are backed up by securing reliability and transparency in water supply to Roodasht and the Gavkhuni wetland, as well as socioeconomic stability and sustainability in the region.

From the point of view of the authors, the use of the action plan is only successful if tackling the challenges in Roodasht is understood as a national task. In this context, the fundamental requirements are:

- A firm political will to solve the problems in Roodasht and the basin. This includes taking a number of urgent political decisions and a persistent support of the implementation of proposed measures.
- The provision of necessary financial resources.

Parallel to these two essential prerequisites, the government must take clear steps toward confidence building among residents and stakeholders at large. The people in Roodasht have felt marginalized by the government during the past water scarce years and have been lost trust in governmental institutions and authorities. Too often they have felt deprived of their rights and been misinformed. But also committed staff of governmental institutions have been found to be frustrated by the lack of courage and action when it comes to taking and implementing political decisions, and about the poor allocation of financial resources. In this light, the action plan is a chance to unite and link the forces of stakeholders, experts, and decision makers to manifest and pursue a shared idea and vision for the future development of Roodasht and the whole Zayandeh Rud basin.

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Chapter 15
A Short Ecological History of Varzaneh: Adaptive Responses to and Resilience Against the Adversity of Drought

Yuka Nishikawa

Contents

15.1 Introduction

Water is one of the most vital necessities in arid and semiarid lands. Livelihood and subsistence activities are impossible without water. As a result of this, water has become a crucial issue in the Middle East, North Africa, and Eastern Asia. The severe drought of 2000 in arid Eurasian nations caused damage in several dimensions, including socially, economically, and ecologically. The drought severely affected Iran. At that time, the seriousness of water issues in Iran became apparent, specifically at Hamoun Lake, Urumia Lake, and the lower basin of the Zayandeh Rud (which can be translated as "life-giving" [*zayandeh*] "river" [*rud*]). Land

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degradation at Hamoun lake in the Sistan and Baluchestan Provinces progressed to irreversible levels, and many farmers were forced to move to other cities. The lower Zayandeh Rud basin also suffered from serious water shortages over the preceding 15 years. Researchers have specifically identified eastern Isfahan, located in the lower Zayandeh Rud basin, as a particularly severe example. One hundred thousand farmers there lost their jobs because of this disaster and the lack of irrigation in the area (Flotz 2002; Molle and Wester 2009).

On the other hand, as Wilhite and Glantz (1985) argued, droughts are a normal part of the cycle of the ecosystem in arid and semiarid lands, and "aridity" is a part of the lifestyle of these regions. People living in these regions have historically developed means for remaining resilient and enduring these conditions. Extensive traditional adaptations to droughts are apparent in subsistence activities, including water usage, traditional technologies like qanats, and cultural customs related to irrigation. In the city of Varzaneh in the Isfahan Province of Iran, inhabitants have adapted to the aridity and conditions of drought through local ecological knowledge.

Why have droughts become such a serious problem in recent years? Frequent droughts and other water-related issues in the Zayandeh Rud basin have both ecological and socioeconomic causes. According to Torfe et al. (2017), water distribution in the Zayandeh Rud basin is problematic and a subject of ongoing debate. Sheikh Bahaei's scroll, which is the basis for the regulations concerning water distribution in the region, addresses traditional rights to water but does not address such rights for newer stakeholders, such as industrial companies, creating conflict between the two groups. This creates a critical problem during water shortages. It is unclear how long this problem will persist. As Suzuki (2011) reported, The Roodasht region, particularly in Varzaneh, is experiencing an uncommonly prolonged period of drought. The situation continues to worsen despite their struggle. The negative effects associated with drought impact those living in poverty the most. However, they're not abandoning their farmland but trying to keep their lives in the community. The number of inhabitants has not decreased. Their struggles have continued to the present day. How they have responded to the adversity of this unprecedented drought is the core concern of this study.

My aim is to describe how the people of Varzaneh have responded to these droughts by focusing on their subsistence activities. To achieve this aim, I have conducted qualitative research through life history interviews with residents of Varzaneh who are engaged in traditional subsistence activities and have experienced the most trying water shortages in the region.

15.2 Research Field and Method: Writing a Short Ecological History

15.2.1 Previous Studies of Subsistence Activities in Arid and Semiarid Regions of Iran

Subsistence activities in arid regions of Iran have been well researched, especially by Japanese scholars. My research is based on those previous Japanese studies of subsistence that focus on agricultural villages. As many of these have only been published in Japanese, I would like to introduce briefly and review them here before clarifying my own research viewpoint. Before the Land Reform and the Islamic revolution, Ohno (1967, 1996, 1990) conducted intensive field research on a small village, Kheirabad, in Shiraz County from the early 1960s to the 1980s. His research revealed how farmers in the region lived under the landlord–peasant system. Okazaki (1986, 1988) investigated qanats and described their cultural aspects and relationship to the landlord system. He also discussed water use practices and irrigation system of the Zayandeh Rud basin based on Lambton (1938) and Mahmudiyan (1968)'s previous articles. Hara (1997) researched Fars Province and South Khorasan Province, creating the concept of "desert-edge areas," defined as habitable regions on the edges of arid and semiarid lands. All these researchers described how farmers in the small villages of the central plateau of Iran maintain their livelihoods, with special concern for their customs and for qanats. They also indicated that the installation of pumping wells and the abandonment of qanats altered the interaction between human beings and nature, disrupting traditional customs and practices.

The achievements of these previous studies are highly valuable, but they focused heavily on agriculture. Lambton (1953), on the other hand, describes how the farmers in this region usually also engaged in a secondary form of subsistence, namely pastoralism. Pastoralism performed multiple functions for the farmers and villagers (Lambton 1953). Previous Japanese studies have not presented a clear picture of the relationships between subsistence activities as a whole in this specific region. Subsistence activities are usually combined in one of several ways, and in different ecologies, people make use of natural features differently. Previous studies have tended to generalize about subsistence activities, especially agriculture, giving most of their attention to how a specific activity is adaptive, and pay little attention to the mechanisms that connect these various activities. If a proper perspective on a specific region is the aim, a broader perspective is necessary, meaning that some understanding of the relationship or interactions between several subsistence activities is required. Nowadays, there are many current studies regarding water management and water-related problems in the Zayandeh Rud basin. Raber et al. (2017) conducted the research about the vulnerability of farmers and the adaptive capacity in the Roodasht region which is located in the lower basin of the Zayandeh Rud. They depicted the complex situation of farmers and characterized factors and conditions in the link to water scarcity by using qualitative and quantitative data. Though their achievement is highly suggestive, what has not been described specifically, however, is how the inhabitants use the river to cope with and to respond to such severe water scarcity.

I applied resilience theory to the adaptive responses of the residents facing adversity in the lower Zayandeh Rud basin. Walker et al. (2004) defined resilience as the capacity of a system to absorb disturbance and reorganize while undergoing change and retaining essentially the same function, structural identity, and feedback. I have adopted his concept in order to understand dynamic cycles of adaptation to drought through a diachronic point of view.

15.2.2 Research Method

Those elements missing from the previous studies and the concept of resilience from Walker et al. (2004) demonstrate that both spatial and temporal aspects of the history of subsistence living in Varzaneh must be considered. Moreover, to understand the relationship among subsistence activities and also that between subsistence activities and the people, it is crucial for me to examine their lifestyle through the eyes of those conducting these subsistence activities. Therefore, through a semi-structured and life-history and life-story approach (Bertaux 1982, 1984) in Varzaneh, I analyzed the adaptive responses of residents to environmental and social changes. Although the problem of how I should determine which subsistence activities are primary and which subordinate still remains, this study will evaluate this problem based on the scale and time expenditure of these activities.

After gathering these life histories, I wrote a short ecological history of Varzaneh, starting in the 1970s, that present the effects of human-subsistence interaction with nature. Following the transformation of diachronic subsistence activities enabled me to examine the lower Zayandeh Rud basin in relation to Iranian history, society, and ecology. Comparison of the adaptive responses to the drought of the 1970s and 1980s with those evinced since 2000 raises two major questions: How has the subsistence way of life in Varzaneh remained so resilient? How have the people of Varzaneh sustained their agricultural subsistence despite prolonged and unexpected drought?

My field research lasted three and a half months. My research subjects were Varzaneh's farmers and their families, approximately 30 informants (including three female informants) in total. An intensive life-history interview was conducted with seven male informants from this cohort of 30 (Table 15.1).

Table 15.1 Seven male-informant life-history interviews

Name	Age/marital status	Main subsistence	Subordinate subsistence	Field/groundwater accessibility
A	30s Married	Agriculture	Pastoralism	4 ha Accessible
B	60s Married	Agriculture	Pastoralism	10 ha Accessible
C	50s Married	Pastoralism	None	None Inaccessible
D	40s Married	Pastoralism	Agriculture	8 ha Inaccessible
E	50s Married	Animal husbandry	Agriculture	10 ha Inaccessible
F	60s Married	Agriculture	Aquafarming	10 ha Accessible
G	50s Married	Agriculture	Tourism	10 ha Inaccessible

15.3 Life Histories in Varzaneh

15.3.1 Varzaneh: Ecological and Social Features

The Roodasht region is located in the lower Zayandeh Rud basin and has an arid climate. Due to the availability of river irrigation, this area has been historically able to support agriculture for at least 800 years. However, as mentioned above, Roodasht has been suffering from a serious water shortage since the year 2000. This has affected agricultural productivity, leading to a deterioration in living conditions and conflicts over water among the farmers.

In Sheikh Bahaei's scroll, Roodasht has 6 of the 33 major water shares in the basin. These 6 major water shares are divided into 243 minor water shares, with Varzaneh allotted 48 retail water shares in 10 cultivated areas. Subsistence activities in Varzaneh have traditionally been agricultural, but because of groundwater conditions in the last several years, subsistence activities have diversified. In the agricultural fields of Varzaneh, groundwater degradation is visible from satellite imagery (Fig. 15.1). The availability of groundwater depends on one's geographical location, that is, the lower and the farther from the Zayandeh Rud an agricultural field is, the less groundwater is available.

Areas where groundwater is less available, but cultivation nonetheless occurs, are located below the white dotted line in Fig. 15.1. Above this white line, subsistence activities consist of mid-scale agriculture, aqua farming, pastoralism, and animal husbandry. Below the line, subsistence activities consist of pastoralism, livestock husbandry, small-scale agriculture, and tourism. Naturally, within the less rural region of the city, residents are employed as city officers, shopkeepers, drivers, and in other occupations. Some of Varzaneh's women also do subsistence work,

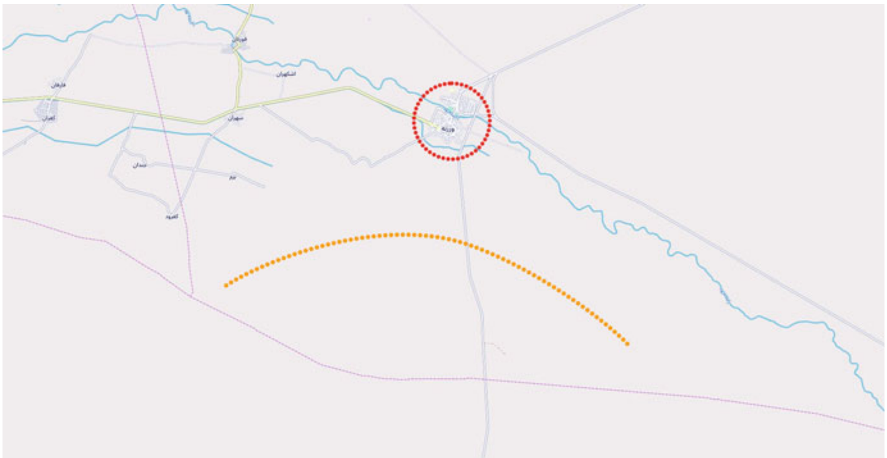

Fig. 15.1 Agricultural fields of Varzaneh (based on OpenStreetMap (August, 2019 viewed) with arrangement dotted line by author)

including the weaving of rugs, carpets, and cloth, whereas others work at city hall or in the school system.

15.3.2 Varzaneh's Recent Adaptive Strategies

Due to unpredictable water supplies in the last several years, farmers have been incorporating artificial reservoirs (called *estakhr*) into their agricultural practices. The level of groundwater has decreased over the past 10 years, and it has not been replenished, to the point that pumping wells are no longer viable. As a result, the farmers have begun using those artificial reservoirs (Fig. 15.2). The procedure was to first pump water from the wells into the reservoir for storage, which was adequate for part of a field if border irrigation was used. Then, the farmers channeled water from the reservoir using plastic hoses and motors. A reservoir's average volume is 430 m^3, and the average storage time is 11 h. To irrigate a quarter hectare requires four hours on average.

In arid regions, the lower basin of a river exhibits soil salinization, as is the case with Varzaneh's soil. Thus, drip irrigation, which is believed to optimize water usage and conserve irrigation water, cannot be employed in this area. Border irrigation is the only means for preventing soil salinization and continuing cultivation. *Estakhr* can easily be installed. Because of this simplicity of installation, they are widely utilized throughout Varzaneh and the lower Zayandeh Rud basin. In general, these reservoirs are privately owned.

15.3.3 Subsistence Activities in Varzaneh

Before land reform in the 1970s, plots were cultivated by small landlords. Some farmers did own their own land, but many agricultural peasants did not and worked for the landlords instead. After land reform, these laborers acquired lands of their own. This study sheds new light on the dynamics of agriculture and other subsistence activities in Varzaneh.

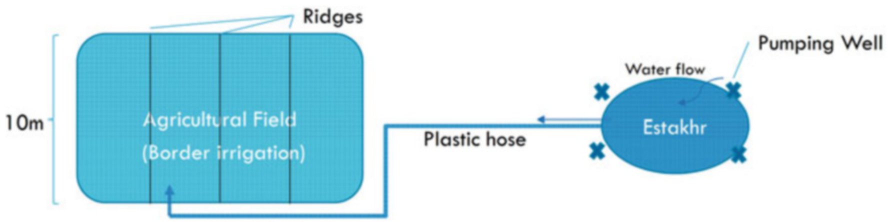

Fig. 15.2 The outline drawing map of Estakhr (artificial reservoir) and irrigation flow

15.3.3.1 Agriculture: The Cases of A and B

Mr. A lives in the groundwater-accessible region of Varzaneh. He is a farmer in his 30s and comes from a family of traditional farmers. His main form of subsistence is agriculture, and he considers himself a farmer. He owns 4 ha (Fig. 15.3 and Table 15.2) that produce mainly wheat, cotton, corn, and alfalfa, along with a private vegetable garden, 40 sheep, and 2 milking cows. Mr. A also engages is pastoralism and animal husbandry. His family has owned livestock on a small scale since the 1950s, when Mr. A's father purchased them. In order to adapt to long-term drought, he increased the number of his livestock and acquired cows for milking. Agricultural machinery is beginning to see widespread usage in the basin, which reduces labor costs and working hours, making stock-farming possible at intervals.

Agricultural productivity has been deteriorating, and it is uncertain from year to year whether irrigation water will be available. In the last several years, he has made

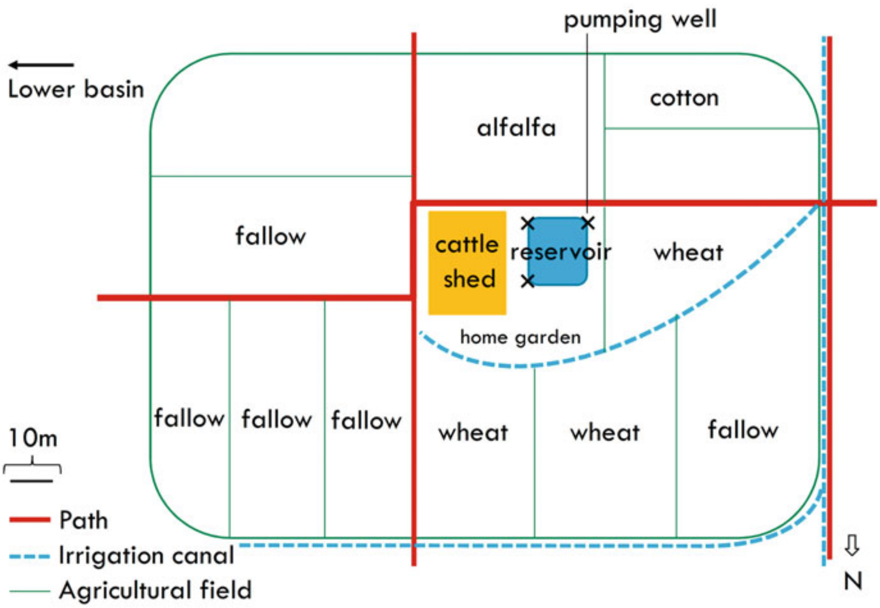

Fig. 15.3 The outline drawing of Mr. A's agricultural fields and farm products in September 2017 (based on my fieldwork and interviews in September, 2017)

Table 15.2 Agricultural calendar in Varzaneh (based on my fieldwork in September, 2017)

Agricultural calendar	Spring (3/21–6/20)	Summer (6/21–9/20)	Autumn (9/21–12/20)	Winter (12/21–3/20)
To Plant	Maize, cotton, sugar beets		Wheat, barley, sugar beets	Wheat, barley, alfalfa
To Crop		Wheat, barley, maize, sugar beets	Cotton	Sugar beets

almost no income from agriculture, but his livestock help to alleviate the risks and uncertainties. Milk is a daily stable source of income, and livestock can be sold for extra income if needed. In addition, he and his family sustain themselves on what their land and livestock can produce in order to remain cost-effective. In other words, in ordinary years when water is adequate for irrigation, his main form of subsistence is agriculture, with pastoralism and husbandry serving as subsidiary forms of subsistence.

The hot, dry climate of Varzaneh produces a single crop during spring and summer and a second in summer and autumn, if water is accessible. Sadly, more than half of the land is fallow because of the current drought conditions. Consequently, Mr. A utilizes his or his neighbor's fallow land as pasture for their livestock. Ecologically speaking, this combination of subsistence activities (feeding livestock on one's own agricultural land) helps to fertilize the land with the residue of such agricultural products as straw. This is common in the arid regions of the west and central Asia. However, because of the stagnation in agricultural productivity, livestock feed must be purchased for some years. This has in turn decreased the productivity of pastoralism.

Mr. B practices a combination of subsistence activities. Mr. B owns larger fields and a greater number of livestock and also has more relatives working with him than Mr. A does.

15.3.3.2 Pastoralism: The Cases of C and D

Mr. C is a pastoralist in his 50s who lives in a groundwater-inaccessible region. He and his family, including his father and grandfather, are traditional pastoralists. His son and other relatives now work alongside him as well. They possess a few fields, a cattle shed, and 200 sheep and 200 goats. Table 15.3 shows how a family like that feeds their livestock in Varzaneh.

It is noteworthy that in spring (spring in the Iranian calendar, based on the Gregorian calendar, lasts from 21 March until 20 June) they take their livestock to the vast wilderness located in north-eastern Varzaneh (Fig. 15.4). During those 3 months, they move roughly once every 10 days to allow their cattle to graze on wild grass. Thus, the family can be classified as seminomadic, a tradition of the family's for at least 60 years. If Mr. C's grandfather or father had journeyed to the wilderness, they would not have been able to return home even once for the full

Table 15.3 Pastoralism calendar in Varzaneh (based on my fieldwork in Sep, 2017–Feb, 2019)

Pastoralism calendar	Spring (3/21–6/20)	Summer (6/21–9/20)	Autumn (9/21–12/20)	Winter (12/21–3/20)
To Feed	Semi-nomadism (Wild grass, Bushes)	Alfalfa Maize Sugar beets	Cotton residue Wheat or barley Straw (Semi-nomadism: depending on climate)	Alfalfa Sugar beets Wheat or barley Straw

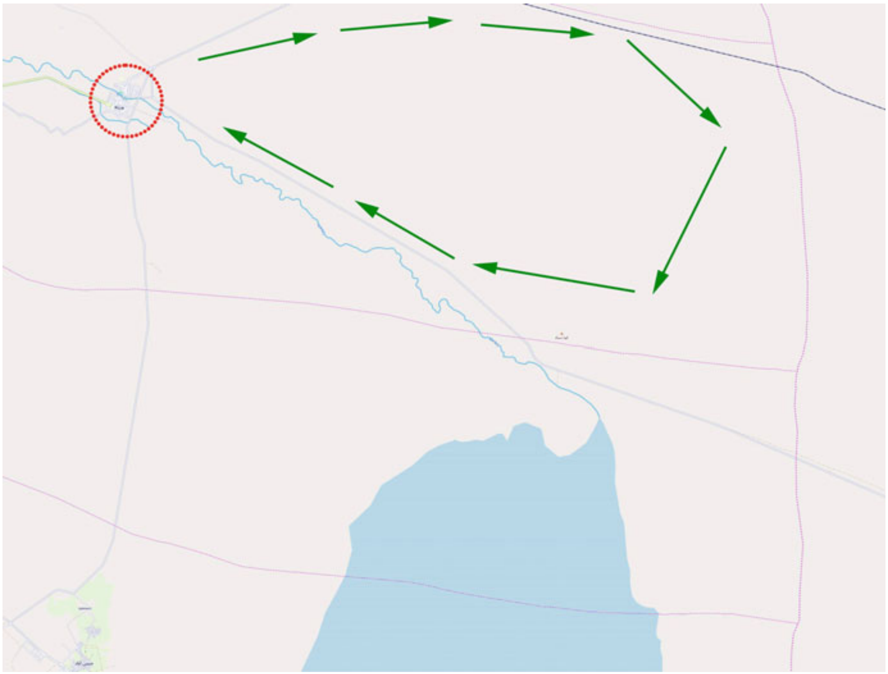

Fig. 15.4 Varzaneh's pastoralists' semi-nomadism route in summer (This route has not been changed historically. Based on OpenStreetMap (2019 August viewed) with arrangement dotted arrow by the author.)

3 months. However, because of their vehicles, family members can now return home once a week in shifts. If rainfall is good, they will take their livestock to graze a second time in autumn. After these seminomadic activities, they bring their livestock back to Varzaneh, to their fallow land or the harvested land of other farmers, paying a fee (which is shared by the family) for allowing their livestock to graze and to feed agricultural crop residues in the summer and autumn (Table 15.3). In winter, fields are usually barren or seeding, so there are no remnants of agricultural products available. Instead, Mr. C's family feed their livestock stored wheat or barley straw or rent fields where another farmer has planted, for instance, alfalfa.

During this period of drought, the family has been forced to purchase and haul feed from another province. To afford this feed, they have had to sell a number of livestock. Mr. C's main form of subsistence is pastoralism, with semi-nomadism as a secondary form of subsistence. Semi-nomadism may seem redundant, but it is a risk-avoidance strategy that helps protect the family's livelihood. The wilderness (in Persian: *biaban*) is neither occupied nor managed, and so, no one maintains the pasturage. Semi-nomadism is tough work, but allows Mr. C's family to feed their livestock in spring and autumn without either paying fee or consuming their stores of straw.

Mr. D is a pastoralist with fields located in a groundwater-inaccessible region. Because of the particularities of his fields, when the amount of water he receives through irrigation is sufficient, he plants livestock feed, such as alfalfa. He grazes his livestock on his own fields and in the wilderness.

15.3.3.3 Different Combinations: The Cases of E, F, and G

Mr. E combines husbandry and agriculture. He owns 10 ha of agricultural fields (Fig. 15.5) and his field is located in a groundwater-inaccessible region. Though his strategy is similar to Mr. D's, there is a clear difference between semi-nomadism and animal husbandry. Cattle husbandry was not common in Varzaneh. Both Mr. D, Mr. E, and their families were traditionally farmers and pastoralists, but because of the unavailability of arable land, Mr. E focused on husbandry (milk cows and butchery).

Mr. F combines agriculture with aquafarming. He is traditionally a farmer, and his land is located in a groundwater-accessible region, so he has convenient access to irrigation. There are two large artificial reservoirs (*estakhr*) on his land, in one of which he farms trout. The aquafarming in the Varzaneh may seem odd in the first place, but in their life-history, the experiences and practices with river fishes did exist. Thus, it could be said that fishery was somewhat involved in their subsistence at that time.

Mr. G lives in a groundwater-inaccessible region. He is a farmer from a family of traditional farmers. Previously, he cultivated wheat, cotton, and corn, but not in the last 10 years, as the amount of groundwater pumped into his reservoir has decreased. Mr. G has been forced to fill half of his reservoir, but his agricultural situation has not improved. When river water is available, a small part of his field can be cultivated. His wife has been weaving rugs to supplement their income but the price of rugs has

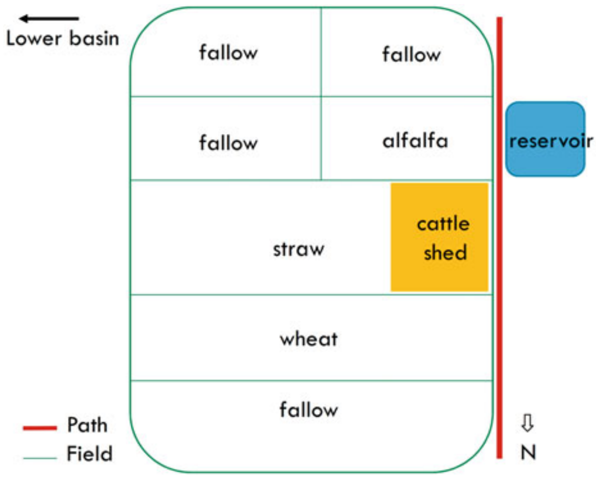

Fig. 15.5 Mr. E's outline drawing agricultural fields (Based on my fieldwork in February 2019)

fallen significantly. Consequently, Mr. G decided to build a tourist facility on his fallow land and start a business through loans from other farmers. The business is an exhibition of traditional agricultural tools.

As described above, there are several ways of combining subsistence activities to respond to prolonged periods of drought. Generally, new sources of income are not traditional subsistence activities, but for most residents the foundation of at least one of their sources of income is a traditional subsistence activity.

15.4 Discussion: The Resilience of the Subsistence Way of Life in Varzaneh

In the previous section, I dealt with typical cases of residents living a subsistence way of life in Varzaneh. In this section, I will describe the characteristics of subsistence. There are several adaptive ways of combining and diversifying subsistence activities. From these life histories, it is clear that, for at least 50 years (from the 1970s onward), the main form of subsistence for Varzaneh's people has been agriculture, with pastoralism as a subsidiary form of subsistence. Although the balance between agriculture and pastoralism depends on the family, and most residents consider themselves farmers. However, from a diachronic viewpoint, this balance has been inconsistent, meaning that, whenever droughts occur, farmers will preference other forms of subsistence. Moreover, in reference to Lambton's work (1953), the subordinate form of subsistence, which is commonly pastoralism in agricultural villages, played the same role in the 1930s and 1940s, and this practice, passed on from generation to generation, has continued to play this role until today. For example, selling livestock in times of drought in order to supplement their income, or using livestock manure as fertilizer for their field, are practices that have been done throughout about over nine decades.

In addition, from an ecological viewpoint, agriculture and pastoralism in Varzaneh rely on one another, which is clear from the way that the seasonal run of events in each domain intertwines (Table 15.4). This study has demonstrated the close ties between agriculture and pastoralism. Such phenomena have been observed in previous studies of subsistence activities in arid or semiarid regions. Especially since 2000, when water shortages have become serious, the people of Varzaneh have responded by altering their sources of water, altering their methods of irrigation, prioritizing other forms of subsistence, and combining economic activities. However, these activities have both direct and indirect connections with the available quantity of river water. There are clear differences in the relationship between the Zayandeh Rud and each subsistence activity depending on how it is linked to water supply and usage.

It also could be said that the adaptive responses to drought in Varzaneh have not changed that drastically as a result of the severe drought in 2000 and its aftereffects. Strategies for dealing with drought have been informed and formed by a long history

Table 15.4 The connection between the agricultural calendar and pastoral calendar in Varzaneh

Agricultural calendar	Spring (3/21–6/20)	Summer (6/21–9/20)	Autumn (9/21–12/20)	Winter (12/21–3/20)
To PLANT	Maize, Cotton, Sugar beets		Wheat, Barley, Sugar beets	Wheat, Barley, Alfalfa
To CROP		Wheat, Barley, Maize, Sugar beets	Cotton	Sugar beets

Pastoralism calendar	Spring (3/21–6/20)	Summer (6/21–9/20)	Autumn (9/21–12/20)	Winter (12/21–3/20)
To FEED	Semi-nomadism (Wild grass, Bushes)	Alfalfa, Maize, Sugar beets	Cotton Residue Wheat or Barley Straw (Semi-nomadism: depending on climate)	Alfalfa Sugar beets Wheat or Barley Straw

Note: Alfalfa is perennial. Pastoralists and farmers in Varzaneh are feeding it to their livestock whenever it grows, especially in summer and winter. Wheat and barley straw tend to be stocked for winter

of interaction between nature and human beings, which has created traditional practices that foster resilience against aridity. This resilience is a token of individuals who have survived the struggles of war, droughts, and economic sanctions. It is highly significant that the stories and lifestyle of inspiring examples of human resilience have been recorded.

15.5 Conclusion

What does the “diversifying subsistence activities of Varzaneh” mean in the context of progressing climate change? The transformation of subsistence activities in other arid and semiarid lands has indicated that, as land degradation progresses, the more subsistence activities will come to depend on pastoralism. Moreover, previous studies, such as Conacher (1982), concerning the salt tolerance of livestock and agricultural products in arid conditions have proved that livestock have a greater salt tolerance. For example, sheep can ingest salinized water, but sugar beets and maize do not grow well in the same salinized water. We might infer that the diversifying subsistence activities and the process of land degradation are signaling desertification. If degradation does not stop or slow, Varzaneh and the traditional practices and knowledge found there might be irreversibly damaged, and Varzaneh might become increasingly vulnerable and dependent on other provinces.

How might these vulnerabilities be lessened and resilience be further empowered? In my case studies, I inferred that Varzaneh's resilience was based on their historical experiences of being raised with subsistence practices, including a strategy of redundancy. Such extant traditional practices must be encouraged and strengthened. The lower Zayandeh Rud basin itself has a dual character of resilience and vulnerability. Because of the river, the agriculture of Varzaneh has been sustained for over 800 years, but because of its location, the city is now facing difficulties that the upper basin is not. The key causes of today's drought and environmental issues have been pointed out oftenly as the water inefficiency and overuse of agricultural practices and the inadequate crop pattern in arid and semiarid lands, by a number of Iranian scholars, like Madani (2014), Madani et al. (2016), Yazdandoost (2016) and Tahbaz (2016). They have argued that water management and water distribution for agriculture in arid lands must be changed fundamentally, and they also suggest that we need to empower farmers and rural communities. However, without understanding their practices and livelihood at macro-level, and with water distribution changing drastically, how could we empower them? How will the inhabitants of Varzaneh survive? Agriculture is an indispensable part of pastoralism in Varzaneh, so if one vanishes, the other will eventually vanish as well.

Other areas that do have more access to water should note the adaptive and maladaptive strategies the people of Varzaneh develop in response to the long-term drought, and the effects they will have on the city's future. I conclude that, in reconsidering water management in the region, attention must be given not to agriculture alone, which depends directly on the availability of water, but also to what links the various subsistence activities in each area with the river and agriculture. The Zayandeh Rud flows through a variety of ecologies, from mountainous areas to a desert wilderness, and past a variety of social environments, from large cities to small villages. Undoubtedly, there are many ways for local subsistence activities and ways of life to interact and combine. We must be aware of the relationship between the Zayandeh Rud and the subsistence activities of the upper and lower basins; moreover, we should design the proper use and management of the river for the entire basin by analyzing its details.

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Chapter 16
Determination of Net Water Requirement of Crops and Gardens in Order to Optimize the Management of Water Demand in Agricultural Sector

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16.1 Introduction

16.1.1 Problem Statement

In Iran, the average annual precipitation is approximately 240 mm. However, it is temporally and spatially uneven distributed, therefore it does not optimally match the crops growing season's duration. Hence, water shortages are frequent, especially during the crop growing seasons. Iran, subjected to frequent droughts and water shortages, the water productivity of the agricultural sector must be improved by the management of existing water resources. Due to the lack of sufficient rainfall and unfavorable temporal and spatial distribution, Iran ranks among the arid and semi-arid countries in the world with serious water shortage problems (Keshavarz et al. 2005). This is compounded by a high population growth rate during the last four decades that has caused an increase in water demand for the limited water resources. The recent severe droughts caused by climate change in Iran brought forward many problems for agriculture. For example, production of rainfed wheat and barley dropped by 34–75% (OCHA 2001). Agriculture in Iran is highly dependent on irrigation water, as around 80% of agricultural product comes from irrigated crops (Salemi et al. 2011).

The high water demand of the agriculture and urban sectors in the study area, downstream of the ZRB (especially the Roodasht region) located in the central part of Iran; is intensified by the limited natural availability of water resources, arid conditions, and climatic variability. The main problem in the ZRB, particularly in the

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upstream area, is the higher consumption of water resources where it provides a lower equitable contribution to economic development (Salemi 2012). Some of the general problems of the agricultural sector in such a study area can be summarized as follows:

Increased food demand due to growing population.

1. The amount of water allocated to the agriculture sector is likely to be reduced due to increasing domestic and industrial demand.
2. The main hydrological planning problem in these regions is due to limited water resources, which is aggravated by the arid condition rainfall and climate variability.
3. Climate change leads to Global warming, which consequently affects water resources, water and soil quality, soil moisture, evapotranspiration, rainfall frequency, type of precipitation and its intensity, and all of these, cause a permanent water shortage in the region directly or indirectly.

In recent years, due to the occurrence of frequent droughts and excessive water shortages in arid and semiarid regions, researchers' attention has been increasingly drawn to the determination of the net water requirement of plants at different phenological stages. Determining the exact timing of the phenological stages of plants allows us to manage the irrigation water (Bodner et al. 2015). Timing of phenological stages of plant growth are a major component in determining crop water requirements in a given area. The phenology of a plant is influenced by various environmental phenomena such as temperature, water availability, and photoperiod. Today, plant modeling is widely used in many sciences, such as climate change assessment (Menzel et al. 2006), and prediction of pest and disease outbreaks (Herms 2004), therefore, it is sometimes known as an integrative environmental science.

The effects of climate change on plant phenology, and in particular the impacts of temperature on these changes over the past decade have been considered. Crop water requirement and WP are those that are affected by climate change and generally lower crop production is expected with global warming due to the limited water supply (Chen et al. 2010).

Other modifying effects are changing the length of the growing period, variation in planting time, and altering cropping patterns (Keshavarz et al. 2010). The greatest concern of the Iranian farmers is the risk of water scarcity and drought (Keshavarz and Karami 2012). The negative effects of climate change are associated with economic and social problems. Unfortunately, small farmers receive the most damage in this regard.

Investigating the effects of climate change on crop water requirement in Iran's ZRB showed that crops water demand for wheat, barley, corn, and rice has been increased (Gohari et al. 2013). The maximum values of net water requirement increased 30.2% and 24.9% for rice and corn, respectively. Similarly, in China, an increase of 15.6–21.8% has been reported for irrigation water requirement of crop production due to warming effects on evapotranspiration under climate change (Tao and Zhang 2010). Other research has examined the effects of climate change on wheat production in Iran. According to this research water deficits during the growing season (autumn to spring) in Iran's wheat-producing areas are expected to increase from 5.2% in 1980 to over 23% by 2050 and 38% by 2100 (Roshan and Grab 2012).

The current debate on climate change impacts on the water cycle has raised concerns regarding future water availability in Central and Northern European countries (Weatherhead and Knox 2000). In the Mediterranean regions, where conditions are expected to become warmer and drier over the next century, reduced rainfall, longer growth period, and delayed flowering and aging are expected (Llorens and Penuelas 2005). Such a profound change in the plant's phenology in dry and semiarid areas means an alarm for the supply and management of water resources. The accurate estimation of irrigation demands under current conditions is therefore a key requirement for better water management under climate change (Maton et al. 2005).

The dryland areas of the study region are characterized by considerable weather variability, as well as major environmental stresses, in particular drought and cold. Due to differentiation of agroclimatic diversity, zoning of different areas needs to take water management into consideration. In view of the very diverse climates, an agroclimatic zone map is of vital importance to achieve this purpose. In this way in this study, an agroclimatic zoning map is presented for better water management. Changes in crop water requirements and a holistic approach and zoning are needed.

Water saving using new irrigation systems and enhanced irrigation management is out-canceled by increases in cropping lands, hence appropriate solutions are necessary to limit water consumption for sustainable agriculture. Isfahan water authority allocates water allocation rights to farmers to manage water delivery (Anonymous 1993) that is the basis for estimation of irrigation water consumption. Nevertheless, there is no knowledge and accounting of irrigation water consumption in agricultural sector. Additionally, competition with irrigators' demand for water has intensified by accelerated population growth, industrialization, and urbanization. To efficiently manage the use of the available water resources to meet the possible variation of cropping patterns, studies of crop water requirements for crops and gardens based on dual coefficients are crucial.

The official organizations report (Anonymous 2005) claims that a portion of all abstracted water from aquifers and the Zayandeh Rud River is illegal and unrecorded. Exhaustive knowledge of irrigation water use is also missing in the Roodasht area, and due to the organizational complexity of public agencies in combination with private water supply companies, accounting for total water sources is out of control of water authority (such as Mirab Company).

16.1.2 Modeling Literature Review

Deterministic models have been developed to estimate crop irrigation needs for assisting irrigation scheduling and water resources management (Wriedt et al. 2009).

In this section, only a few studies that relate to the current study were assigned. Bastiaanssen et al. (2007) provided a complete review on the irrigated crops modeling which focuses on some examples of model applications and technical improvements.

Ramazani-Etedali et al. (2009) applied the CROPWAT model to simulate wheat and barley yield reduction caused by water stress under semiarid conditions in the Karaj Province in Iran. Toda et al. (2005) believed that because the CROPWAT model did not take into consideration different water stress types and the effects of crop response, it is necessary to include these aspects for improved accuracy when estimating dry season irrigation.

Irrigation strategies should be carefully chosen to optimize crop productivity, while guaranteeing the sustainability of agriculture. Todorovic et al. (2009) found out that AquaCrop performed similarly to CropSyst and WOFOST when simulating the water use and yield of sunflowers, but in WP simulation was much better under a limited water supply. CropSyst had a limiting factor in severe water deficit conditions due to utilizing crop growth modules that could be affected by climatic characteristics. Heng et al. (2009) showed that the AquaCrop model performed suitably for the water requirements of maize and grain yield in the non-water-stress treatments and mild stress conditions. But it was less satisfactory in simulating severe water-stress treatments, particularly when stress occurred during senescence. The authors believed that the effect of severe water stress needs more assessment. Araya et al. (2010) found that the AquaCrop model is valid to simulate barley water accounting and crop yield under various planting dates in Ethiopia. The model could be used in the evaluation of optimal planting time and irrigation scheduling. In this study, barley showed somewhat lower performance under mild water-deficient conditions compared to full irrigation treatment. Farshi (1997) and Alizadeh and Kamali (2007) used the standard modeling approach based on the FAO guideline estimated crop water requirement for selected provinces of Iran. They concluded in accounting water need studies involving all provinces of Iran, that information instruments in all surveyed provinces were considered to be inadequate or to have deficits, resulting in poor knowledge on accounting of the real water use by the agriculture sector. These issues create ambiguity in the accuracy and consistency of reported data.

16.1.3 Field Study

A field study is needed to provide the basic data required for irrigation water management. Silage maize, wheat, barley, sorghum, onion, potato, and cotton as annual crops and orchards including olive, grape, pistachio, and pomegranate are perennial crops in the region and are planted in the agricultural areas for many years. For mentioned crops, field experiments have been performed to develop economic techniques to save agricultural sector's water resources.

Isfahan researchers promoted on-farm water balance as the regular method for determining how much water to apply per irrigation. In order to illustrate the impacts of water deficit on yield and some agronomic characteristics of wheat, a study by Salemi and Afyuni (2005) was conducted as randomized complete blocks design with a split-plot layout and three replications during 3 years (2001–2002, 2002–2003, 2003–2004) in Kabutarabad Agricultural Research Station, Isfahan. Three levels of irrigation including 60, 80, and 100% of water requirements were considered as the main plots and six wheat cultivars as subplots. In this study, Pishtaz cultivar was used as the recommended cultivar for the dry regions.

In the same location, a similar experiment (Mahluji et al. 2006) was conducted on the barley genotype (Karron × Kavir, Valfajr, M-79-4, M-79-7, and M-79-15) during two growing seasons (2003–2004 and 2004–2005) with four irrigation levels in three replicates. Additional field trials were conducted with five irrigation levels of 100%, 90%, 80%, 70%, and 60% of full water requirement in three replicates, respectively (Salemi et al. 2017).

In another experiment, the effects of various water consumptive levels on yields of maize were studied in a randomized complete blocks design using a split-plot layout for 3 years. The short season, maze variety (the single cross 647) was planted in this experiment at the research station (Salemi 2012).

The effect of soil moisture stress at early growth stages on yield and tuber size of commonly grown four potato cultivars (*Marfona, Concord, Agria,* and *Cosima)* was studied in an experiment in the 2006 and 2007 growing seasons. The plots were arranged in split-plot with a randomized complete block design with five irrigation treatments replicated three times (Jalali et al. 2017).

To study the effects of irrigation regimes on the bulb yield of onions, an experiment was conducted during two growing seasons (2012 and 2013) (Salemi 2013). The experiment design was Split-Factorial with a randomized complete block arrangement and four replications. The main plots included three irrigation regimes based on evaporation from class A pan and subplots of a factorial combination of two spring onion genotypes (Sweet Spanish and Dorcheh).

An experiment was conducted on a cotton farm at Kabutarabad Research Station (Jafaraghaei and Dehghani 2010) to study the effects of four applications of irrigation water on cotton yield (Tabladila and B-557 cultivars). The experimental design was a complete randomized block with four replications and was conducted in 2 consecutive years (2003–2004).

The results show that regarding the irrigation water requirements for Silage maize, wheat, barley, sorghum, onion, potato, and cotton are 728, 606, 522, 620, 922, 650, and 1150 mm, respectively.

The NWR (Net Water Requirement) model estimates the crop water need in the Roodasht area and validated using meteorological and crop data from experimental fields run by the Isfahan Agricultural Research, Education and Extension Organization. It is believed that policy makers should carefully choose crops and irrigation strategies to maximize the value of the crop yield, while guaranteeing the sustainability of water supply.

The purpose of creating databases and intelligent processing of information is to provide the final output of the project (net water requirements) as follows:

- Provide a basic and upgradable database of soil, climate, and cultivated crops.
- Preparation of calculation algorithm based on output from upgraded database.
- Preparation of dynamic and permanent maps related to net water requirement by the studied plants.
- Generate dynamic reports of net water demands in hydrological and political geographical boundaries.

The scope of this study includes:

1. Selection of the Roodasht region as a major river sub-basin in the ZRB with adequate agronomic and climatic data.
2. Collecting of hydrological and meteorological data, crops, soils, farming practices, and economic data, for the database.
3. Determining the parameters required as input data set for running the simulation and optimization models.
4. Calculating net irrigation water requirements using the NWR model (without any crop water stress).

This project focused on the opportunities for improving agricultural water management through accounting of precision irrigation water requirements. This is a multidisciplinary and integrated approach involving irrigation engineers, soil scientists, agronomists and plant physiologists, and computer experts.

16.2 Materials and Methods

To develop a suitable and practical NWR, various data sets including land suitability and farm information are required. We applied the NWR model by including the crop growth, climate, soil, and irrigation sub models to calculate NWR in the ZRB and Roodasht. Available regional statistics on crop distribution and crop cultivation areas with spatial data sources on soils, land use, and climate were integrated. The required information in a systematic process was summarized and processed into a database for running the NWR mathematical model.

16.2.1 The Study Area

The Zayandeh Rud River (literally, the river that renews itself) has been the lifeblood of central Iran for centuries, focused around the ancient city of Isfahan. In 1600 AD, Isfahan was one of the ten largest cities in the world, sustained by irrigated agriculture and the flows of the Zayandeh Rud River. The city remains the cultural heart of Iran. In this section, an overview of the river basin is provided that helps to put more

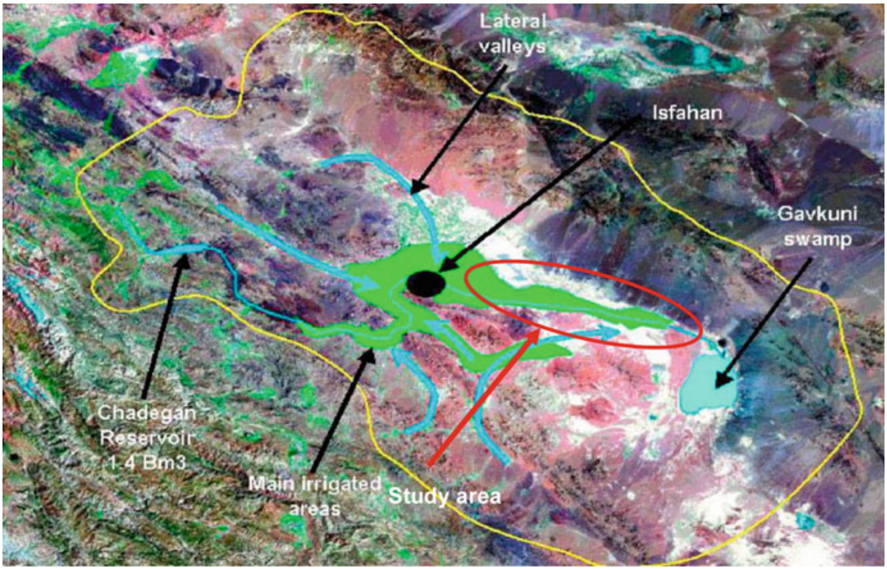

Fig. 16.1 Layout of the ZRB and the location of the study area

detailed information into perspective. The ZRB (Fig. 16.1) has for centuries provided the basis for important economic activities. These activities can be categorized into three sectors including agricultural, industrial, and domestic consumptions. Numerous water projects have been constructed, are under construction or under the study for the basin. The dam is the main water reservoir with 1500 MCM capacity and has been operating since 1971 (Salemi et al. 2011). Modern surface irrigation started in the 1970s with the completion of the Chadegan reservoir and the construction of major diversion dams that serve to regulate the water supply to six irrigation networks namely Lenjanat, Nekooabad, Abshar, Borkhar, Mahyar, and Roodasht (Fig. 16.1). The most part of the ZRB located in the east of Isfahan city along with the Roodasht area is considered as the study area.

The Roodasht irrigation project (52° lon. 32.5° lat.) is located east of Isfahan in the central part of Iran and has an altitude of approximately 1500 m (Fig. 16.2). The climate is arid with temperatures ranging from 35°C in summer down to 3°C in winter. Average annual precipitation is 100 mm. Soils in the area are alluvial deposits and are fine textured, which will result in a total command area of approximately 47,000 ha (Droogers and Torabi 2002).

16.2.2 Site Description

The basin's general soil map is shown in Fig. 16.3. It is evident that in two major subbasins the major soil class is clay while loam is the dominant soil type in other

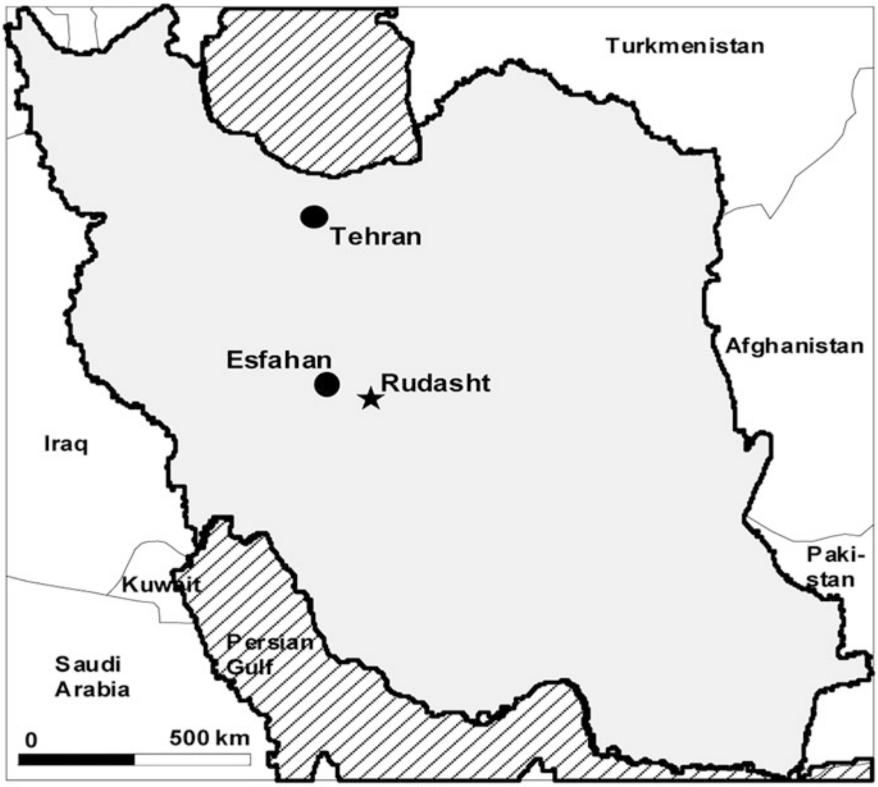

Fig. 16.2 Location of the Roodasht area in the Esfahan region, Iran

subbasins (Anonymous 1998). The figure also shows the soil texture classes of the major irrigation network.

Agriculture is the dominant water user that consumes around 80% of the river yield. However, there has normally been inadequate water to irrigate the total cropped area. Many cropping alternatives are available to farmers in this area. Typically, there is a two-season cropping pattern in all of the irrigation systems on the eastern side of the ZRB. Summer crops include potato, onion, cotton, sorghum, and maize while winter crops are dominated by wheat and barley. In addition, there are some perennial crops, including orchards with olive, grape, pistachio, and pomegranate. Wheat, rice, barley, fodder, and potato are the main staple crops in the basin (Anonymous 1993). The irrigation season commences on 1 April and reservoir releases remain more or less constant from May, June to August. It is only in the later parts of the irrigation season (August to September) that discharges are decreased as demand drops. The providing of more water with timing better suited to the needs of higher value crops has clearly been highly beneficial and productive at basin level and for the upper portions of the ZRB. Yet it has had severe effects on the groundwater problems in the tail part of the river basin, which has led to greatly

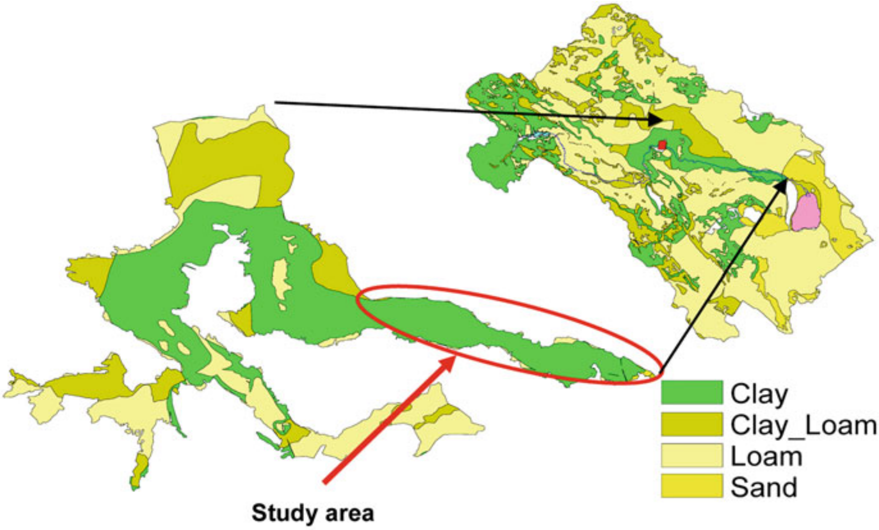

Fig. 16.3 The general soil map of the ZRB and study area (source: Droogers and Torabi 2002)

increased inequity in production and incomes between head and tail end parts of the basin. Recently, due to the intensification of the water crisis along the entire ZRB, no water has been allocated to the Roodasht area. Annual cropping intensity is about 85% and is slightly higher for summer than winter crops. The cropping pattern is dominated by wheat (62%) and barley (9%). No other crop exceeded 10% of the total irrigated area. These cropping patterns are typical of current practices still found in the lower parts of the basin and throughout Roodasht.

16.2.3 Reference Evapotranspiration Calculation Method

Many methods are available for estimating reference evapotranspiration (ETo). The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as ETo. The reference surface is a hypothetical grass reference crop with specific characteristics. The use of other denominations such as potential ET is strongly discouraged due to ambiguities in their definitions Radiation, modified Penman, Blaney–Criddle, and Pan-evaporation, have been broadly applied in different climatic conditions to calculate ET_0. DehghaniSanija et al. (2004) found the Penman–Monteith model as the most reliable method, compared to lysimetric data, for Karaj region, in Iran. Mostafazadeh-Fard et al. (2009) determined crop coefficient and evapotranspiration for a reference crop of grass and for two typical landscape trees of Ash and Cypress using field drainage lysimeter in an arid region of Isfahan in the central part of the country. They demonstrated that the Penman–Monteith FAO 56 method showed good agreement with the lysimeter data. The relatively accurate and consistent performances of the Penman–Monteith approach in both arid and semiarid climates have been indicated in both the American Society of Civil Engineering and European studies (Allen et al. 1998).

In the first stage, reference evapotranspiration was calculated based on the FAO Penman–Montith method using effective parameters by a climate sub-model of the NWR model. This method is the most general and widely used equation for calculating daily reference ETo that is recommended by FAO. Using the Kriging method in GIS environment ETo zoning 13680-time series of temperature and 13680-daily time series of evapotranspiration was simulated for 24 districts and 59 major plains. The spatially distributed implementation covers the Roodasht on a 7 by 7 km grid and the ZRB. The ETo was calculated by applying NWR climate sub-model. In NWR model the ETo, is atmosphere evaporative demand. The inputs for the calculator such as [maximum air temperature (Tmax), minimum air temperature (Tmin), maximum relative humidity (RHmax), minimum relative humidity (RHmin), sunshine hours (n/N), and wind speed at a height of 2 m (u_2) based on long-term weather data (1979–2017) were collected at Kabutarabad station (51.83 lon. 32.5° lat.). Daily reference evapotranspiration was obtained by the Penman–Monteith model (Allen et al. 1998):

$$\mathrm{ETo} = \frac{0.408\,\Delta(R_\mathrm{n} - G) + \gamma\left(\frac{900}{T+273}\right)\mu_2(e_\mathrm{s} - e_\mathrm{a})}{\Delta + \gamma(1 + 0.34\mu_2)} \tag{16.1}$$

where R_n is the net radiation (MJ m^{-2} day^{-1}), G the soil heat flux density (MJ m^{-2} day^{-1}), T the air temperature at 2 m height ($^\circ$C), u_2 the wind speed at 2 m height (m s^{-1}), e_s the saturation vapor pressure (kPa), ea the actual vapor pressure (kPa), e_s–e_a the saturation vapor pressure deficit (kPa), D the slope of the vapor pressure curve (kPa C^{-1}), and γ the psychometric constant (kPa C^{-1}).

The main menu of the climate module is composed of three sections of database management, selected climatic station, and ETo calculation. The climatic parameters are used to calculate ETo, meteorological records can be updated, specified and plotted, and results can be exported into an irrigation sub-model.

16.2.4 Factors Determining the Crop Coefficient (K$_{cb}$ *and* K$_e$)

Typical crop coefficients, calculation procedures for adjusting the crop coefficients and for calculating crop evapotranspiration are presented in this section. There are two calculation approaches: the single and the dual crop coefficient approach. Differences in evaporation and transpiration between the cropped and the reference grass surface can be combined into one single crop coefficient (K_c) or separated into two coefficients: a basal crop (K_{cb}) and a soil evaporation coefficient (K_e) according to the FAO method. K_{cb} of FAO was obtained during a field visit and Eq. (16.2) K_e was calculated from soil physical properties, irrigation intervals, and irrigation depth ($K_c = K_{cb} + K_e$). As discussed in the FAO report No. 56 (Allen et al. 1998), the single crop coefficient approach is used for most applications related to irrigation scheduling, strategy, and management. The dual crop coefficient approach is related to detailed estimates of calculations of soil water evaporation, such as in real-time irrigation scheduling applications.

The growing period can be divided into four distinct growth stages: initial, crop development, mid-season, and end season. The changing physiological characteristics of each crop or tree over the growing season affect the K_c coefficient. Evaporation as a non-benefit part of crop evapotranspiration is soil evaporation and effect K_c. Crop coefficients are dynamic parameters in time and space. The dynamicity of these coefficients is due to ever changing used plant cultivars and species, differences in climate conditions and changes in each region, and dynamism of plant growing seasons due to environmental conditions. These facts reflect the difficulty of crop coefficient application in crop pattern developing programs every year in, yet, a single location (Kuo et al., 2006).

For specific adjustment in climates where RH_{min} differs from 45% or where u_2 is larger or smaller than 2.0 m/s, the K_c mid-values are adjusted as:

$$K_{cb} = K_{cb(FAO)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{16.2}$$

where u_2 is the mean value for wind speed at 2 m height during the mid-season (m/s); RH_{min} is the mean value for minimum daily relative humidity (%) during the midseason; and h is the average plant height (m). Typical values of $K_{cb\ mid}$ for non-stressed conditions in subhumid climates are provided by Allen et al. (1998) and the K_{cb} was calculated for estimation of the crop water evapotranspiration.

16.2.5 Soil Data and Information

To infer soil data and information in net water demand calculations and describing the presented map layouts, three kinds of soil data were used in this study.

- Choropleth maps of soil characteristics mapped based on land units produced for Isfahan province.
- Quantitative soil data extracted from the Isfahan Soil Database (prepared by authors).
- Analyzed soil samples texture, field capacity, and wilting point taken from soil Ap horizon during the field visits.

Some selected soil data in this project were calculated as follows:

- From the Choropleth maps the polygon map of soil types, depth, texture, sand, silt, clay, OC, EC, gravel, and land arability classes are produced.
- Using an additional 1600 soil profile available data, the texture, amount of sand, silt, clay, OC, and EC in two surficial soil layers were interpolated with geostatistical techniques (Toomanian 2016).
- Selecting 204 representative fields of crops and orchards well spread throughout the entire province, disturbed, and undisturbed soil samples were sampled from the surface layer. Soil moisture and bulk density (ρb) of undisturbed samples were measured (ρb were corrected based on the amount of gravel in soils). Soil salinity, texture, amount of sand, silt and clay, OC, gravel, and θw (weighted moisture) of soil FC and PWP of disturbed soils were also determined.
- Having θw and ρb, the θv (volumetric moisture) of soil samples was calculated (Hillel 1980) using the USDA model, the ρb of all profile points was calculated.
- A pedotransfer function was extracted by relating the θv and soil physical parameters (which were all geographically mapped in the study area). This was used to calculate the raster map of θv in the study area.

16.2.6 ETc: Crop Water Requirement

Accurate estimation of ETc in cultivable lands is necessary for improving irrigation scheduling and efficient use of water resources. The most commonly used method for calculating water demand (crop evapotranspiration, ETc) is a two-step approach that calculates ETc from ETo and crop growth through the K_c coefficient (Allen et al. 1998).

The daily ETo is used to calculate the crop evapotranspiration under standard conditions (Kuo et al. 2006), as given by.

$$\mathrm{ETc} = (K_{\mathrm{cb}} + K_{\mathrm{e}})\,\mathrm{ETo} \tag{16.3}$$

where ETc is the crop evapotranspiration (mm day^{-1}) under no soil water stress with adequate soil fertility. At this stage of study, the NWR model is used to calculate ETc and net water requirement during the growing season for each decade in a corresponding month, considering data such as crop coefficient, canopy cover index, crop evapotranspiration, and effective rainfall.

According to the available data, the sub-model irrigation of the NWR model, estimates effective rainfall by the soil conservation service (SCS) relationship. The part of precipitation that directly meets the water need of a plant is called the effective rainfall. Khaleghi (2016) reported that in arid and semiarid areas, the SCS provides more reliable values. Net irrigation requirements per hectare are calculated as the difference between the crop evapotranspiration and effective precipitation.

16.2.7 Agroclimatic Zoning of the Study Area

The dryland areas of Iran are characterized by considerable climate variability, as well as major plant physiological stresses, in particular drought (Ghaffari et al. 2015). Hence an agroclimatic zone (ACZ) map is of vital importance to achieving an applicable approach that provides useful information such as crop suitability for decision makers on a study area scale. The aim of this part of the study is to present agroclimatic zoning differences for crop suitability usages and to indicate easily available information to users and decision makers.

Data of monthly averages of precipitation, temperature, relative humidity, total incoming solar radiation, and wind speed from the main stations (31 synoptic weather stations) were collected in the province from 1978 to 2017 and analyzed by using the UNISCO approach (Ghaffari et al. 2015). Finally, map zoning (ACZ) on the basis of the three criteria: moisture regime, winter type, and summer type provided a total of five agroclimatic zones in regional scale.

16.2.8 Creating an Intelligent Processing System

In order to create an intelligent processing system for provincial water information and to achieve the objectives of this study, a system called "Net Water Requirements Database of Plants in Isfahan Province" was designed and implemented. In this database, the necessary forms for loading all primary information were designed and implemented. In addition, computational algorithms based on the methodology provided by other study groups (soil, water, and plant study groups) for the intelligent processing of these data and calculations related to the water requirement of the studied products were developed and implemented to produce raster maps of each crop. The expected outcomes were also defined in the program. This system allows the users at levels of the researcher, expert, manager and planner, and even the agricultural operator to produce the results as per their will.

In the last part of the study, the combination of field—river basin scale models (NWR) and GIS methods allows estimating irrigation water demands in irrigation districts at a regional scale. This model is linked to a spatial database containing information connecting the soils, weather, and crop physiologic stage, irrigation parameters, and cultivated crop areas for each grid cell. The net irrigation requirements for each 5 climate zone, and for the 11 dominant crops within each grid cell, were calculated using the NWR auto-irrigation model.

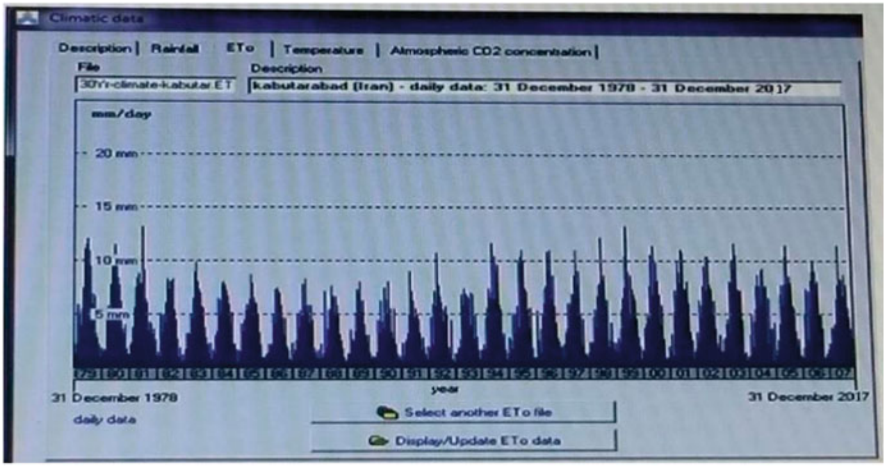

Fig. 16.4 ETo computed from daily meteorological data for Kabutarabad station (1978–2017)

16.3 Results

Based on what had been explained in the methodology section, the results of model output and their associated discussion of processes are presented in this section. In this section of the study ETo, ETc, and net irrigation requirements for each cell and crop are determined and presented.

16.3.1 ETo Outputs

ETo was derived from the long-term Kabutarabad weather station's data (20 km east of Isfahan city) data by FAO Penman–Monteith equation for the Isfahan city presented in Fig. 16.4. In the study area, the ETo rises to 13.6 and 14.8 mm day^{-1} in late May and mid-July, respectively. In the ETo calculator sub-model, the data from a weather station was specified in 11 crop seasons, meteorological data was imported and the calculated ETo was exported to the NWR model.

The total ETo in long-term mean decade (1978–2017) was 1609 mm compared with 1639 mm in 2017. The long-term mean decade ETo was computed for all months and stations. However, iso-ETo curves for each of the 11 active crop growth months, March–October, were illustrated (Fig. 16.5) on Isfahan province's map. It was found that the pattern of these curves is considerably similar from decade to decade. The rate of change of ETo varied from month to month. The monthly ETo increased from April to August, however, the rate of increase was faster than previous (April to June) months. Figure 16.5 shows the long-term mean annual ETo isopleths of the study area. The mean annual ETo for over 30% of the province's area was more than 2000 mm. In the same way, for about half of the province's area

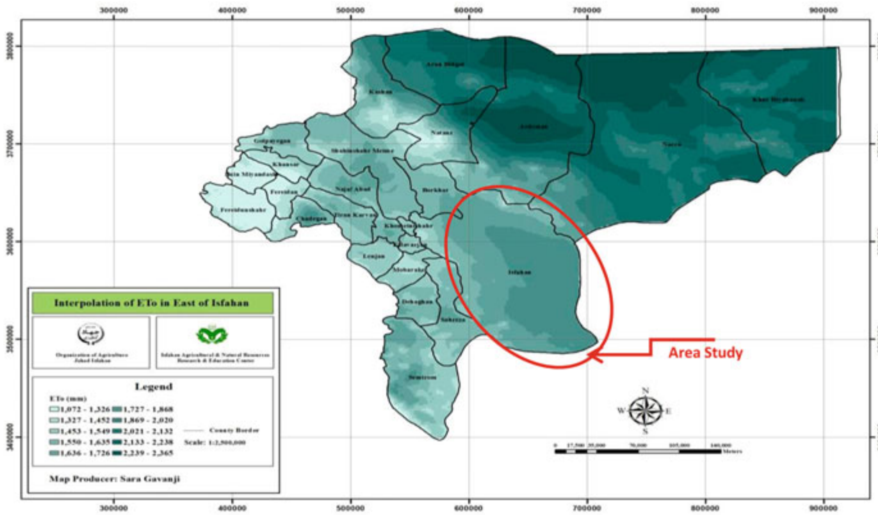

Fig. 16.5 Mean decade ETO (mm) in Isfahan city (1978–2017)

the mean annual ETo was more than 1470 mm. The mean annual ETo of Isfahan province varied between 1219 mm in the Booien-Miandasht station, located in the west, and up to 2027 mm in the Khoor-Beeyabanak station, located in the eastern part of the province.

16.3.2 Agroclimatic Zoning of Isfahan Province

Data of monthly averages of precipitation, temperature, relative humidity, total incoming solar radiation, and wind speed from the main stations (31 synoptic weather stations) were collected in the province from 1978 to 2017 and analyzed by using the UNISCO approach. Finally, map zoning (ACZ) on the basis of the three criteria: moisture regime, winter type, and summer type provided a total of five agroclimatic zones in region scale containing Arid-Cool A-C-VW, A-C-W, A-K-W, SA-C-W, and SA-K-W.

The agroclimatic zones map of Isfahan province has been obtained from one of the outputs of the study (Fig. 16.6). The classes were created using a program written in Visual Basic. The ACZ map is of vital importance to achieving an applicable approach that provides vital information such as crop suitability for decision makers on a study area scale.

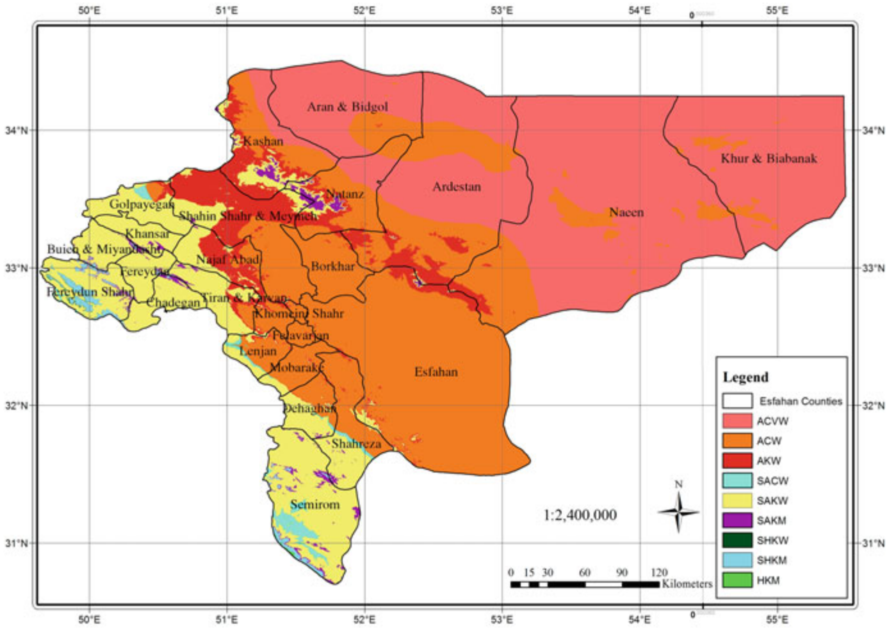

Fig. 16.6 Agroclimatic zones

16.3.3 Net Water Requirement

This part focuses mainly on NWR results which can be used as a useful tool for irrigation water demand analysis and deficit irrigation implementation in agricultural water management in study areas east of the river basin.

To compute the net water requirement for the seven crops during the growing season, the irrigation schedule is defined on the basis of fixed intervals (time criterion) between irrigations (overall 7–8 days) and back to soil field capacity options as depth criterion was considered. Model output was presented at 10-day intervals (i.e., decade). After completing the data entry by other information groups using the implemented algorithms, the ETo reference, the plant's net water requirement (ETc, effective rainfall), and finally the irrigation requirement was calculated and mapped as geographic raster outlines.

These maps were produced for 36 decades for 1987–2017 growing session. Raster maps of net water requirements are reported, and all calculated data and information are produced in five climatic zones. The decade water requirement for

Table 16.1 Calculated irrigation water requirement of wheat in the region

Month	Decade	E (mm)	Tr (mm)	ET (mm)	Rain (mm)	NWR (mm)
11	2	10.5	0	10.5	0	0
11	3	5.7	0.3	6	1	0
12	1	1.4	1	2.4	0	0
12	2	2.2	1.5	3.6	0	2.6
12	3	6.5	3.7	9.8	0	9.8
1	1	5.4	4.8	10.1	0	10.2
1	2	3.2	4.7	8	0	7.7
1	3	3.9	10.3	14.2	0	15.3
2	1	5.2	14.5	19.7	5.1	14.1
2	2	2.5	18.5	21	0	20.4
2	3	2.7	21.4	24.1	1	25.4
3	1	3.2	27.1	30.3	3.6	27.5
3	2	3.6	32.1	35.8	6.4	29.2
3	3	2.2	33.7	35.8	0.6	33.5
4	1	1.7	28.1	29.8	3	25.7
4	2	1.9	30.2	32.3	0	34.4
4	3	2.8	49.7	52.6	10	43.2
5	1	2.4	49.7	52.2	1	53.9
5	2	2.9	54.6	57.4	2	55.2
5	3	4.3	57.2	61.7	0.10	59.5
6	1	6.2	32.9	39	0	38.8
6	2	10	6.2	16.4	2.8	14.4
Total		91	483	574	38	520.8

E: Evaporation, Tr: Transpiration

the annual crops is given in Tables 16.1, 16.2, 16.3, 16.4, 16.5, 16.6, and 16.7 where E is evaporation from the soil and Tr is the crop transpiration, decade is the three 10-day intervals of the month.

In addition, the ETc, rain effect, and NWR during the growing season were estimated using the NWR model for the four garden crops at the study locations. In the pomegranate, pistachio, grape, and olive gardens, the net water requirements during the growing session resulted in 908, 703, 728, and 512 mm, respectively. To validate the results' net water requirement, experimental data, the irrigation management model was applied for estimating crop water requirements and upgrading irrigation management for the 11 crops east of the ZRB.

There are two distinguished cropping seasons in a year in the study area: the summer season and the autumn season. In the summer season, all crops need irrigation water from April to October. In order to allocate irrigation water to each crop, the value of net monthly water requirement for all productions per unit area is

Table 16.2 Calculated irrigation water requirement of barley in the region

Month	Decade	E (mm)	Tr (mm)	ET (mm)	Rain (mm)	NWR (mm)
11	2	10.6	0	10.6	0	5.1
11	3	2	1.8	3.8	1.2	2.6
12	1	3.8	1.4	5.1	4.5	3.4
12	2	2.7	2.7	5.3	5.4	0
12	3	3.1	2.5	5.6	12	0
1	1	2.8	2.7	5.7	12.2	0
1	2	3.4	3.8	7.2	12.1	0
1	3	2.6	10.3	12.9	4.6	7.3
2	1	2.3	14.4	16.7	3	5.7
2	2	2.8	25.2	27.9	1.2	25.0
2	3	1	26.1	27.1	0	21.5
3	1	2.1	40.7	37.7	3.3	31.2
3	2	1.1	34.7	30.7	5.7	25.6
3	3	1.5	48	44.6	0	44.8
4	1	1.7	43	40.7	11.3	30.9
4	2	1.8	41.4	38.2	12.6	30.9
4	3	1.2	53.1	49.2	4	45.5
5	1	1.8	62.9	58.8	1.7	55.5
5	2	3.7	63.3	62.0	0	62.8
5	3	8.5	20.2	28.5	0	28.5
Total		62.5	498.2	518.3	92.8	426.5

Table 16.3 Calculated irrigation water requirement of silage maize in the region

Month	Decade	E (mm)	Tr (mm)	ET (mm)	Rain (mm)	NWR (mm)
6	1	22.4	0.3	22.6	0	9.2
6	2	34.6	2.5	37.1	0.5	24.9
6	3	33.6	7.4	40.7	0	42.4
7	1	30.1	41.3	71.3	0	71.6
7	2	10	77.5	87.5	0	88.1
7	3	3.3	98.7	102.1	0	102.2
8	1	2.3	94.7	97.2	0.6	93.9
8	2	2	87.6	89.5	0	88.4
8	3	3.1	77.7	80.8	0	81.5
9	1	8.2	48.6	57	2.2	55.4
9	2	5	4.6	9.6	0.3	7.1
Total		164.6	545.9	710.4	3.6	665.7

Table 16.4 Calculated irrigation water requirement of *Sorghum* in the region

Month	Decade	E (mm)	Tr (mm)	ET (mm)	Rain (mm)	NWR (mm)
6	1	10.4	0.3	10.7	0	10.2
6	2	28.6	2.5	31.1	0.5	30.9
6	3	27.6	7.4	35.0	0	35.4
7	1	24.1	26.3	50.4	0	50.4
7	2	4	62.5	66.5	0	66.1
7	3	3.3	83.7	87.0	0	86.2
8	1	2.3	79.7	82.0	0.6	81.9
8	2	2	72.6	74.6	0	74.4
8	3	3.1	62.7	65.8	0	65.5
9	1	2.2	33.6	35.8	2.2	33.4
9	2	2	4.6	6.6	0.3	6.1
Total		110.0	445.9	564.4	4.4	540.0

Table 16.5 Calculated irrigation water requirement of potato in the region

Month	Decade	E (mm)	Tr (mm)	ET (mm)	Rain (mm)	NWR (mm)
4	1	10.1	0	10.1	0	0
4	2	14.9	0	14.9	4.3	0
4	3	9.6	0.4	10	0.2	12.5
5	1	22.7	3.4	26	0.2	22.9
5	2	25.9	10.6	36.7	0	33.9
5	3	18.5	30.4	49	0.8	51.1
6	1	5.7	44.7	50.5	0	43.1
6	2	1.4	45.9	47.2	0	50
6	3	0.1	51.1	51.2	0	44.9
7	1	0	51.7	51.7	0	48.8
7	2	0	56	56	0	52.6
7	3	0	51.9	51.9	0	54.2
8	1	0	44.4	44.4	0	45.2
8	2	0	41.5	41.5	0	41.9
8	3	0	45	45	0	46.8
Total		108.9	477	586.1	6	547.9

illustrated in Table 16.8. The evapotranspiration for winter wheat crop was the lowest (426.5 mm) and the summer crop onion was the highest (1107.7 mm).

Graphical displays of local average crop water requirement for 11 crops in the period 1978–2017 are shown in Figs. 16.7, 16.8, 16.9, 16.10, 16.11, 16.12, 16.13, 16.14, 16.15, and 16.16.

Table 16.6 Calculated irrigation water requirement of onion in the region

Month	Decade	E (mm)	Tr (mm)	ET (mm)	Rain (mm)	NWR (mm)
3	1	13.2	0	13.2	0	0
3	2	25.6	0.5	25.9	2.9	23.8
3	3	43.2	1.4	44.7	7.8	36
4	1	37.1	2.5	39.8	0.2	39.8
4	2	35.4	5.4	40.9	1	41.5
4	3	38.6	11.4	50	1.7	48
5	1	37.8	23.5	61.1	0	62.2
5	2	30.6	40.6	71.2	0	70.7
5	3	22.7	50.2	73.1	1	72
6	1	22.9	63.7	86.4	0	86.4
6	2	20.3	65.4	86.1	0.2	86.7
6	3	22.3	75.7	98	0	96.5
7	1	22.1	78	100.2	0	101.9
7	2	20.3	72	92.2	0	92.5
7	3	20.9	74.7	95.6	0	94.3
8	1	17	60.9	77.7	0	78.2
8	2	19.3	46.6	65.6	0.3	64.5
8	3	19.6	3.2	22.7	0	12.7
Total		468.9	675.7	1144.4	15.1	1107.7

Table 16.7 Calculated irrigation water requirement of cotton in the region

Month	Decade	E (mm)	Tr (mm)	ET (mm)	Rain (mm)	NWR (mm)
5	1	9.4	0	9.4	0	0
5	2	7.8	0.1	7.9	0.2	4.3
5	3	19.8	1.8	21.5	0	18.3
6	1	20.3	3.4	23.6	0	20.7
6	2	22.3	8.2	30.5	0	30.2
6	3	18.1	15.6	33.8	0	33.2
7	1	16.6	29.5	46.3	0	42.8
7	2	11.1	52.5	63.5	0	65.2
7	3	7.5	98.6	105.9	0	108.6
8	1	3.3	92.6	96.2	0	90.2
8	2	2	88.7	90.7	0	91.8
8	3	1.2	86.7	88.3	0	86.3
9	1	0.9	68.7	69.3	0	70.9
9	2	1	73.9	74.8	0	71.2
9	3	0.8	57.8	58.4	0	59.3
10	1	1	53.1	54	0	50.1
10	2	0.6	25.1	25.4	0	25.6
Total		143.7	756.3	899.5	0	869

Table 16.8 Monthly water requirement (mm) for main crops in study area

Crop	Net water requirement (mm)											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Wheat	0	0	12.4	33	60	90.2	103.3	168.6	53.2	0	0	0
Barley	0	7.7	3.4	7.3	52.2	102	107.3	146.5	0	0	0	0
Sorghum	0	0	0	0	0	0	0	76.6	202.8	221.7	250.6	39.6
Silage maize	62	0	0	0	0	0	0	0	91.5	261.9	263.8	0
Potato	0	0	0	0	0	0	12.5	107.9	138	155.6	133.9	0
Onion	0	0	0	0	0	59.7	129.3	204.9	269.6	288.7	155.5	0
Cotton	75.	0	0	0	0	0	0	22.6	84.1	216.6	268.3	201.7

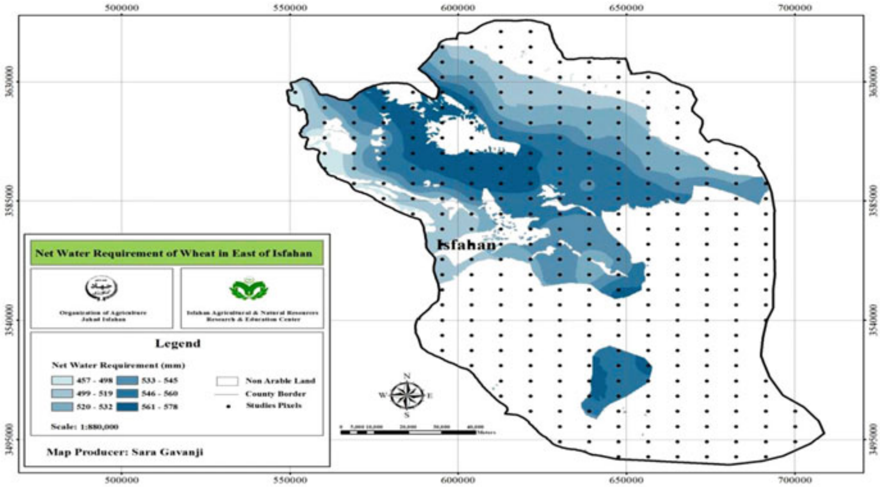

Fig. 16.7 Range of irrigation requirements of wheat (Max–Min) in study area (simulation period 1978–2017)

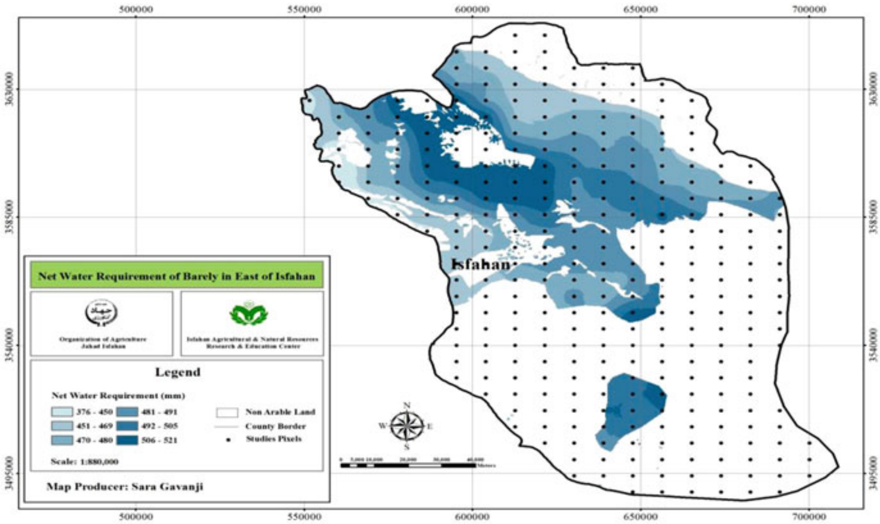

Fig. 16.8 Range of irrigation requirements of barely (Max–Min) in study area (simulation period 1978–2017)

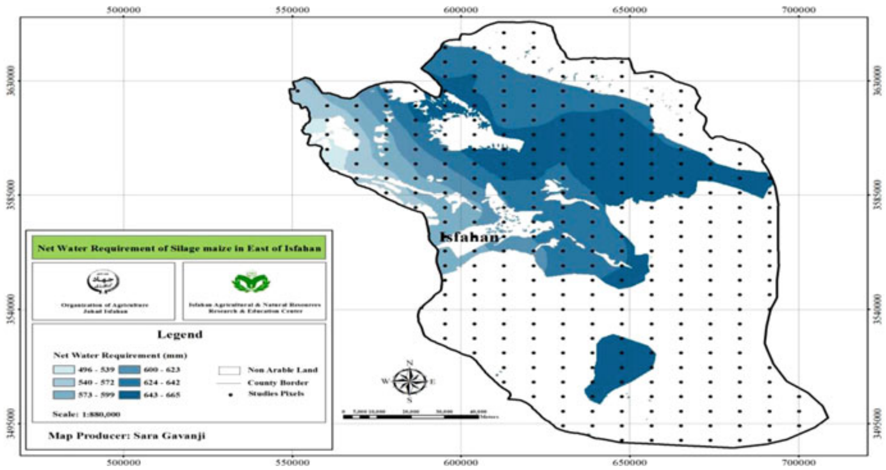

Fig. 16.9 Range of irrigation requirements of silage maize (Max–Min) in study area (simulation period 1978–2017)

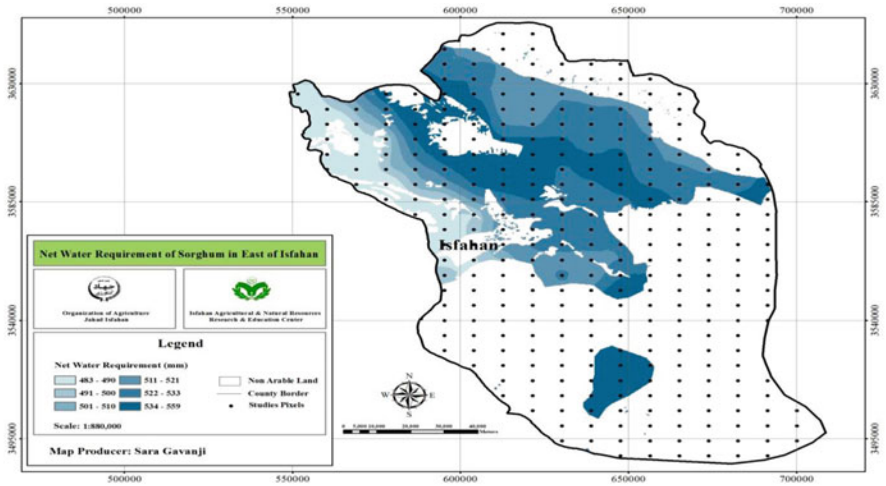

Fig. 16.10 Range of irrigation requirements of sorghum (Max–Min) in study area (simulation period 1978–2017)

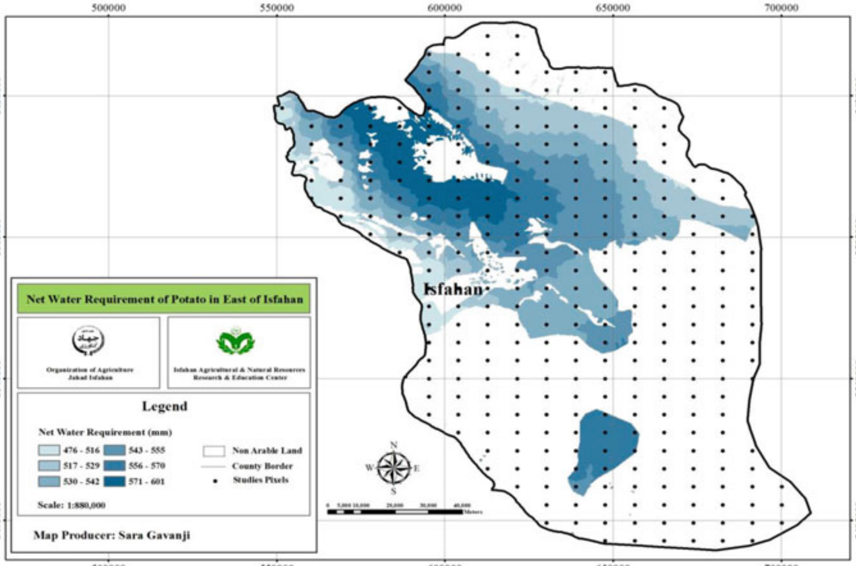

Fig. 16.11 Range of irrigation requirements of potato (Max–Min) in study area (simulation period 1978–2017)

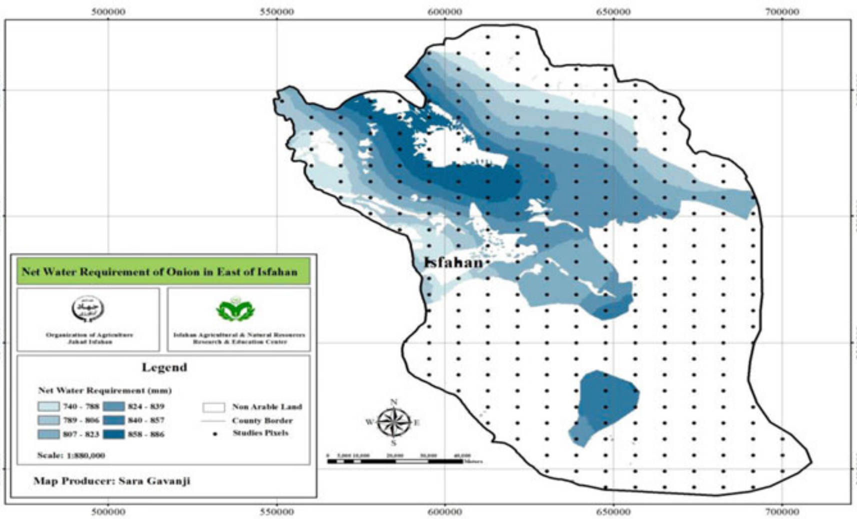

Fig. 16.12 Range of irrigation requirements of onion (Max–Min) in study area (simulation period 1978–2017)

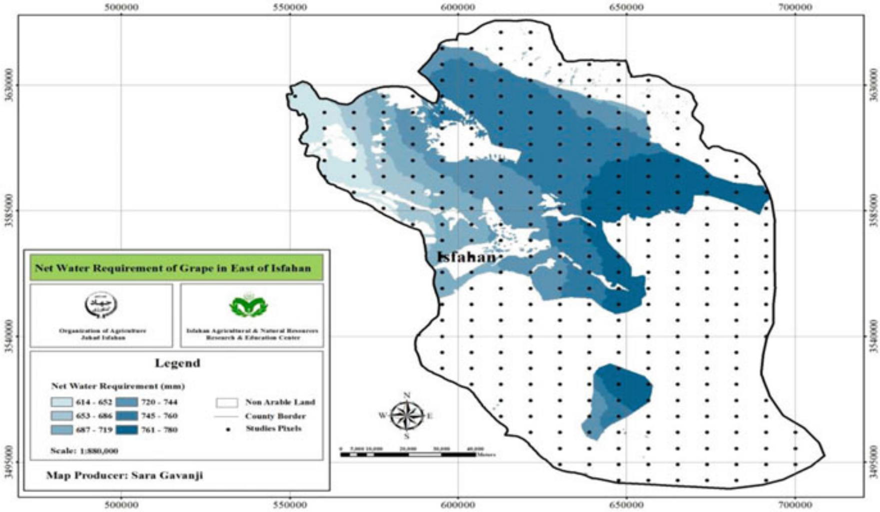

Fig. 16.13 Range of irrigation requirements of grape (Max–Min) in study area (simulation period 1978–2017)

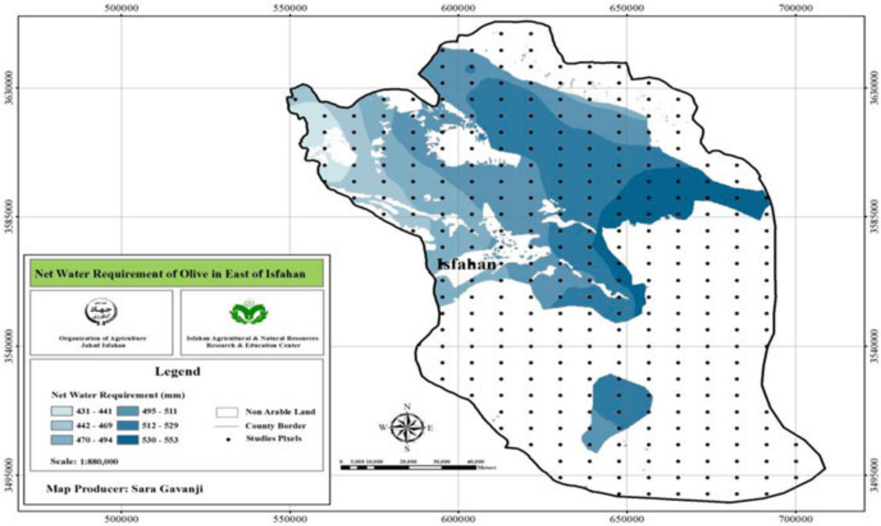

Fig. 16.14 Range of irrigation requirements of olive (Max–Min) in study area (simulation period 1978–2017)

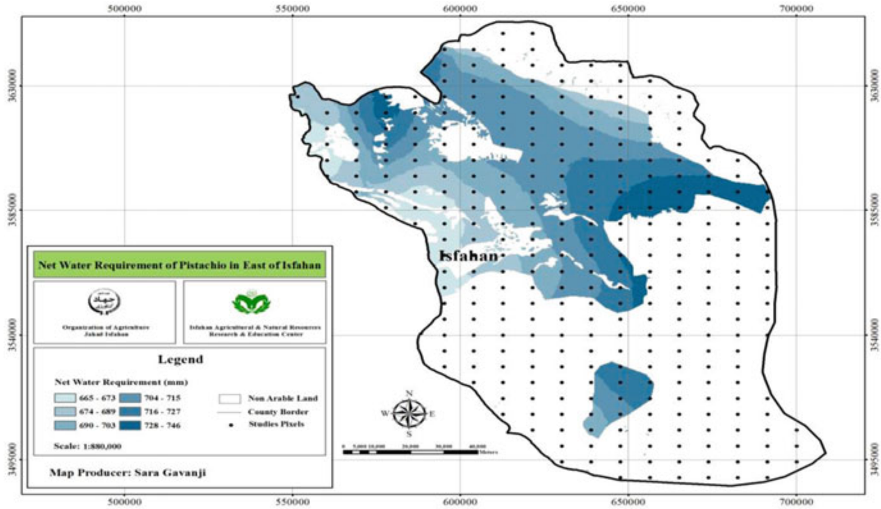

Fig. 16.15 Range of irrigation requirements of pistachio (Max–Min) in study area (simulation period 1978–2017)

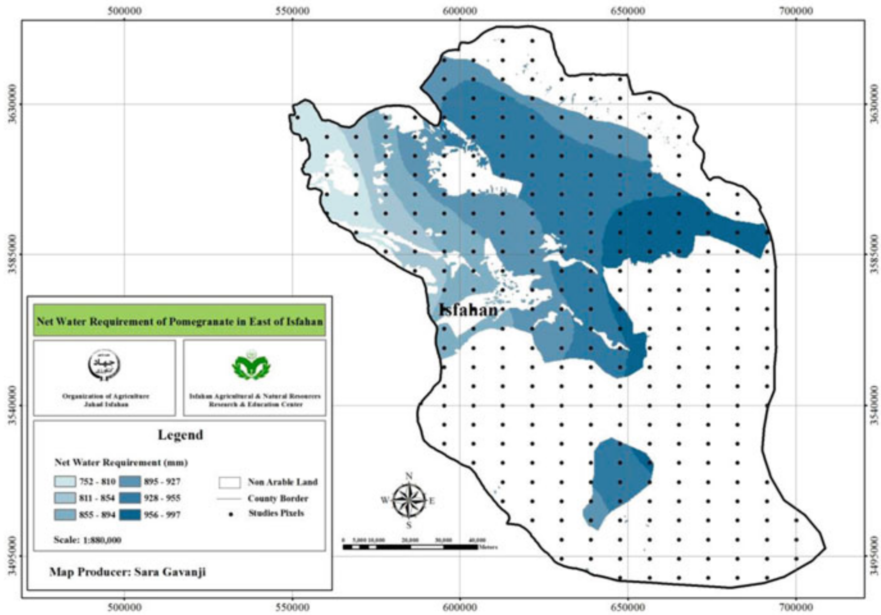

Fig. 16.16 Range of irrigation requirements of pomegranate (Max–Min) in study area (simulation period 1978–2017)

16.4 Conclusion

To meet Iranian food demand, the volume of water allocated to agriculture will have to increase, and by the year 2021 it will exceed 150 BCM, which is 15% in excess of the country's total potential renewable freshwater resources (Alizadeh 2005). Given that Iran is currently using 66% of its freshwater resources for irrigation as compared to a world average of 45% (Mousavi 2005), this increase would be impossible to meet. Irrigation efficiency and water productivity may be increased in the ZRB based on estimates of ETo from the NWR model, by meting the water demand accurately. According to the graph outputs of the ETo amounts, annual reference evapotranspiration varied between 1219 mm in the western region of the province to over 2027 mm in the eastern parts of Isfahan province. It can be concluded that the eastern parts of the ZRB (Isfahan city), which had low amounts of annual rainfall and high annual ETo, are often confronted with water deficits. Crop water requirement in this study refers to the accumulated crop evapotranspiration over the growing period for a certain crop group. Net irrigation requirements estimated by the NWR model are useful for providing balanced estimates on the ZRB's scale. There is a need to assess serious technical irrigation issues in the study area when conflicts between water supply and demand in multiple cropping irrigation schemes arise. In this way, gross irrigation requirements will be estimated at regional level considering the efficiency of irrigation methods as future studies.

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Chapter 17
Increasing Water and Energy Productivity via Replacing Abiotic Stress Tolerant Forages in East of Zayandeh Rud River Basin

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Contents

17.1 Introduction

Considering rapidly increase in demand of water for industry, domestic and environmental purposes, and water availability for irrigated agriculture will decrease in future in many parts of the world, especially in the arid and semiarid regions (FAO 2017). With growing demand for water in agriculture and in order to fulfill food security objectives, and moreover, competition across water-using sectors for more water, has faced world with the challenge of producing more food with less water (FAO 2017). This goal will be met only if appropriate strategies are sought for water savings and for more efficient use of water in agriculture (Molden 2006).

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Climate change and drought are an inevitable climatic reality, which not only reduce the allocation of surface water and underground water but also caused the greater salinity of water in Zayandeh Rud River Basin such as Roodasht region, so that the crop production in study area seems not to be sustaining (Torabi et al. 2018). Hence, it is needed to make a special focus on increasing water productivity by optimum water allocation in the cropping pattern and applying irrigation water management (Salemi et al. 2018). During the last few years, the volume of water provided by the Zayandeh Rud River has been variable and not enough to fulfill all water demands in the agricultural area. Therefore, strategies need to be developed for time of water distribution, the amount of water in every allocation, and replacing abiotic stresses tolerant crops (Torabi et al. 2018).

Roodasht region located in the east of Isfahan city consists of rural areas, which is the farmers in these areas are smallholder and all aspects of farmers' lives depend on agriculture. In farming livelihood, forage production, keeping domestic animals and dairy production to meet the household's nutritional needs is very important. A decade ago in Zayandeh Rud River Basin without any water restrictions, alfalfa and corn silage have been the supplier of livestock fodder, which are regarding water limitation the production of previous forage crops has been severely restricted, and replacing drought-tolerant forage crops is a necessity (Torabi et al. 2018; Salemi et al. 2018).

Sorghum (*Sorghum bicolor*) as one of the most adapted crop to drought, low requirements to chemical fertilizers and pesticides, soil fertility, and biotic stress, is a suitable alternative to corn. Some s*orghum* cultivars such as *brown midrib* (BMR) are similar to corn in terms of nutritional value whereas its water productivity is superior to corn in arid and semiarid regions (Borba et al. 2012; Neto et al. 2017). Nowadays, there is more interest in forage of s*orghum* than corn due to high water productivity, drought-tolerant, improving nutritional quality through decreasing of lignin and high digestibility in BMR cultivars, which has become more important in many regions of the world where drought is common and water availability for irrigation is limited or restricted (Bernard 2016; Neto et al. 2017).

17.2 Water Productivity

Water productivity is one of the indexes of optimal use of irrigation water, which is increased through adopting optimal cropping pattern and extension of drought-tolerant crops area (Hussain et al. 2007). However, increasing water scarcity has led to the development of the concept of water productivity expressed in yield per applied irrigation at farm level (Cai and Rosegrant 2003). One important strategy to water scarcity is to better manage the water and increase the productivity of water. The determination of water productivity index for main crops in Iran is essential to obtain suitable methods for better water use in agriculture sector (Heydari 2014). One of the methods for increasing productivity of water consumed in the agriculture sector is through improved water demand management (Heydari 2014). The most common description is "agricultural water productivity from the view point of crop yield." The concept of this description is briefly as follows:

"Productivity from the view point of crop yield: According to this definition, the higher productivity of agricultural water means more production per unit volume of water" (Heydari 2014). The concept of water productivity has become increasingly important, because it can be interpreted in relation to the amount of the obtained yield, the amount of obtained energy, or the amount of financial gain per unit of water consumption in water scarcity situation.

Salemi and Amin (2010) indicated that reducing water flow, loading more than capacity on water resources, inappropriate water distribution management cause unsustained agriculture system in the Zayandeh Rud River Basin, and it needs to revise on water distribution, water allocation, and optimizing in cropping pattern.

Sustainable production of forage for livestock will obtain from cultivation of forage crops such as sorghum with high water productivity due to its ability in maximum water absorption from soil, minimum water loss from plant canopy, and minimum water demand in photosynthesis cycle (through their inherent tolerance to abiotic stresses) instead to forage crops with high water requirement (Bean 2008). Some botanical traits of sorghum such as deep and extant root systems, waxy cover on stem and leaf, ability to maximize WP through leaf arrangement and stomatal regulation cause these crops has been considered as forage crops with high water productivity (OGTR 2017).

Adams and Erickson (2016) reported maintenance of sorghum yield with imposition of water stress (50 and 75% water input of the control) during vegetative growth stage, resulting in improved water productivity. Assefa et al. (2014) demonstrated that more than 36% yield reductions can be experienced with water deficit in vegetative stage, though the authors did state that sorghum was capable of tolerating shorter periods of less severe water stress with minimum yield loss camper to other similar crops. Base on the study in the United States the researchers have shown that forage sorghum can achieve comparable water productivity to corn with less evapotranspiration and water requirement, where the required water was obtained during the growing season for forage sorghum 489 mm and water productivity of 3.5 kg/m^3 (Howell et al. 2008).

17.3 Energy Productivity

Agricultural production is aimed at achieving goals such as using existing potentials and capabilities to meet the minimum food needs of the regions and the countries, creating jobs, and providing appropriate income for agricultural producers (Mohammadian et al. 2007). Increasing population and economic growth have led to an increase in demand for food, excessive pressure on resources, and a lack of proper use of produced resources.

In the production of any agricultural product, there is a cycle or energy flow in which energy is consumed as an input of agricultural inputs, the final product is produced as a transformed energy (food). This energy is invested in various forms such as mechanical (farm machines, human labor, and animal draft), chemical (fertilizer, pesticides, and herbicides), and electrical. Increasing population and economic growth have led to an increase in demand for food, excessive pressure on water and energy sources, and the lack of proper use of produced resources. In this regard, determining the pattern of energy consumption in crop production and estimating energy consumption indices is one of the pillars for modifying the crop pattern in each region. Therefore, it is necessary to study and analyze the energy consumption pattern and its efficiency in agricultural systems. There is a worldwide trend toward increasing consumption of fossil energy in the production of necessary foodstuffs. This energy use creates two problems related to agricultural sustainability. First, fossil energy is a limited resource and will eventually be exhausted. The other problem is that serious environmental impacts are related to energy use such as acidification, higher level of CO_2, eutrophication, loss of biodiversity, soil losses, mining of water, and pollution (Kocheki and Hosseini 1994). Optimization use of energy in agriculture reduces environmental problems and prevents the destruction of natural resources and develops sustainable agriculture as an economic production system (Erdal et al. 2007). For this reason, in the late twentieth century, new perspectives have been introduced in this regard, in view of increasing the efficiency of inputs, environmental protection and natural resources, ecological economics, and, finally, and food security. In this context, systems have been defined under various headings, such as sustainable agriculture, ecological agriculture, low agriculture, organic agriculture, and renewable agriculture (Kocheki and Hosseini 1994).

The energy used in the irrigation process is the main component of energy consumption in crop production. This energy consists of the total energy used to pump water from the depths of the ground and the energy needed to build irrigation equipment. According to existing relationships, the energy used to pump water is directly proportional to the height of the water pump suction and volume of water consumed or water used in agricultural products (Ajabshirchi 2006). Thus, there is a direct relationship between water used efficiency and energy efficiency. According to the definition of water productivity, it is equal to the ratio of the amount of agricultural production and the amount of water consumed. Also, energy efficiency is equal to the ratio of the amount of agricultural production and the amount of energy consumed. On the other hand, a part of the energy consumption is related to the water consumed in the product. In other words, under the same conditions of irrigation, a product with higher water productivity will definitely have higher energy efficiency.

In order to compare different agricultural systems from the perspective of energy, energy indices are estimated including energy efficiency or energy ratio, net energy gain, energy efficiency, and energy intensity. The ratio or energy efficiency, which is the most important indicator of energy evaluation in agricultural systems, is the ratio of total output energy (energy of products) to total input energy (energy of inputs consumed). The net gain energy is equal to the numerical difference between the total produced energy (output) and the total input energy (input). Energy efficiency is also equal to the amount of product produced divided by the total energy consumed

Table 17.1 The results of studies from 2013 to 2018 related to the comparison of energy consumption and energy efficiency of *Sorghum* and corn silage

Crop	Total energy consumption (MJ/ha)	Energy productivity	References
Forage corn	28,472	0.42	Faiazbakhsh and Alizadeh (2018)
	77,589	0.79	Amanloo and Ghasemi-Mobtaker (2013)
	96,233	0.57	Salemi et al. (2018)
Forage sorghum	30,347.5	3.4	Faiazbakhsh and Alizadeh (2018)
	37,695	0.47	Fartoot-Enaiat et al. (2017)
	81,684	1.12	Salemi et al. (2018)

(input) or, in other words, equal to the amount of product produced per unit of energy consumption. Energy intensity index is the amount of energy consumed per unit of the product (Kocheki and Hosseini 1994).

Corn and sorghum silage are two popular forage crops that are used for ruminant animals because of high yield, digestibility, palatability, storage ability, etc. (Torabi et al. 2018). These two important forage crops are comparable in some aspects of agriculture. One of the effective factors to choosing these two crops is energy consumption, in particular energy efficiency, in addition to other factors such as water use efficiency and nutritional value. A product with higher energy efficiency reduces energy consumption in production and reduces environmental hazards. Also, lower energy consumption with higher production, equal to the lower costs, which make production economical. Several studies have been done to compare energy efficiency in corn and sorghum forage products in Iran (Table 17.1).

17.4 Sorghum as Water Productive Forage

Sorghum (*Sorghum bicolor*) is one of the most drought-tolerant crop originated and domesticated in the northeastern part of Africa, including Ethiopia and Sudan regions where sorghum cultivation started approximately 4000–3000 BC. Some other regions such as Nigeria and India are known as the second home of sorghum in the world (Dillon et al. 2007; Devries and Toenniessen 2001). Sorghum is the world's fifth largest most important grain cereal, after wheat, maize, rice, and barley that genetically derived from the wild *Sorghum bicolor* sub.sp. (ICRISAT 2015; Wortmann et al. 2008). The area under cultivation of sorghum in Iran is about 50,000 ha currently, whereas according to the projected plan for and regarding release of high-quality hybrid cultivars, the area under sorghum cultivation will increase to 150,000 ha in the next 4 years. Due to the continuing effects of climate change on forage production a significant reduction in forage products with low water productivity such as maize silage and alfalfa occurred, subsequently sorghum cultivated area is rising as an alternative to high-water forage crops in Iran particularly Zayandeh Rud River Basin.

Sorghum is the only crop that cultivated as multipurpose crop, which provides grain and biomass that can be used for food, fodder, sugar, biofuel, syrup, silage, grazing, and paper (OGTR 2017). Sorghum is grown in a wide range of climates from latitude 50°N to 50°S of the equator, however, nowadays sorghum is suitable replacing forage to low water productivity forages for arid and semiarid areas where water restriction affects agricultural production, and annual precipitation in these areas is usually less than 300 mm/year (Assefa et al. 2014). Based on the rich gene pool of wild sorghum and manipulation of crop breeders, nowadays sorghum adapted throughout a broad range of environments and soils (Sukumaran et al. 2012). Annual global production of grain sorghum is estimated at approximately 60 million tons per year, where the United States is the largest exporter and China is the largest importer of grain sorghum in the world (FAOSTAT 2019). Sorghum and millets are the most important crops that prepare human staple and livestock feed in harsh environment regions due to climate change, whereas more than 500 million people throughout 60 countries feed on grain sorghum (ICRISAT 2015).

One of the big demands for water in agriculture segment is fodder production, something that has undergone a serious problem under conditions of climate change and water scarcity in arid and semiarid areas. forage sorghum cultivars divided from Sudan-grass hybrids, sorghum x Sudan-grass hybrids, sweet sorghum hybrids (*Sorghum bicolor*), open-pollinated sweet sorghum and dual-purpose sorghum grain hybrids can be feed by dairy, beef cattle, sheep, and goat flocks as silage, hay, and grazing form (ICRISAT 2015). Due to global climate change and subsequently intensifying of drought, salinity, and high temperatures cultivation of sorghum replace to some crops like corn with high water demand is in agenda in arid and semiarid regions (Dillon et al. 2007; ICRISAT 2015). Replacing drought-tolerant forage crops with high water productivity such as sorghum is the main strategy dealing with water shortages and increase sustainability in agricultural production in arid regions of the Middle East, especially Iran (Torabi et al. 2018). Bean (2008) demonstrated that there is a significant difference between sorghum cultivars (BMR and non-BMR) and corn in terms of yield production, but in terms of nutrition some cultivars of both BMR and non-BMR sorghum are equal in nutritional quality to corn. Sorghum requires 40–53% less water to produce a crop than corn (McCorkle et al. 2007). Sorghum varieties have more stem, less leaf, and ear compared to corn, that is why the rate of fiber concentrations in sorghum forge is more than corn (Contreras-Govea et al. 2010).

17.4.1 Features Related to Water Productivity and Drought Tolerance in Sorghum

Root systems have the main role of absorption of water and minerals from the soil, to communicate with above-ground parts to maintain water turgidity in the leaves, and subsequently to continue the photosynthesis and production (OGTR 2017). A well-developed root system in sorghum has been achieved from two sections, including seminal root (root seed) and the adventitious crown roots. After germination seminal roots appear from emerge radicle, where seminal roots uptake water and mineral for young plant for 3 weeks till the end of establishment stage, than adventitious crown roots appear from the first node of stem or from several leaf nodes, when plants reach to 4th–5th leaf stage. The development of the sorghum root can extend only up to 1.5–2 m deep, while the horizontal expansion of the sorghum root is very dense and wide (Singh et al. 2010; OGTR 2017). Horizontal development of sorghum root as a dense fibrous layer provides maximum ability to uptake water from the soil, where almost more than 50% of absorbed water is absorbed from a depth of 30–90 cm, so that this ability increase the water productivity and drought tolerance in sorghum compared to other crops (Damavandi et al. 2008; Rostamza et al. 2013). The sorghum root dense such as pad in the surface layer of the soil prevents water penetration into the lower layers, so that the maximum water absorption in the surface layer and minimum water losses increase water productivity camper to other crops. Sorghum roots are thinner than corn and the number of hair roots is two times per square centimeter of soil profile in sorghum compared to corn (Damavandi et al. 2008). Mat like root system due to widespread root system in rhizosphere, cause increase water productivity in sorghum in water shortage period, and capability of sorghum to grow in dryland farming (Fig. 17.1).

Cuticular wax is one of the most innovative features in sorghum, which obtained from natural evolution, and it has a fundamental role against abiotic and biotic stresses. In the sorghum cultivars, the main part of stems and leaf sheaths are covered with wax, which is the covered surface become shiny, and it is a possibility to reflection of sun radiation. The presence of wax layers on the surface of the plant reduces plant temperature and evapotranspiration and consequently increases the water productivity in the sorghum cultivars (Xue et al. 2017).

Feature of stay-green as the ability to maintain green leaves and stems during the grain-filling period is the main factor to increase drought tolerance and water productivity in sorghum cultivars, because due to stay-green and continuity photosynthesis the amount of dry matter will increase, and subsequently water productivity will rose. There are some evidence have shown that features such as root volume, root distribution, leaf architecture, and most importantly green-stay capacity in sorghum have led increasing in the rate of photosynthetic materials transition during grain filling (Borrell et al. 2014).

Tillering in early sorghum growth stages is a valuable ability to compensating for weak establishment in sorghum in harsh environments due to drought and water shortages. Tillering is a proper feature to increasing water productivity in sorghum in

Fig. 17.1 Volume extension of roots in sorghum as one of the features of water productivity in sorghum (photo taken by Dr. Mosavi Fazl H 2014, Engineering Research Department, Semnan Agricultural and Natural Resources Research and Education Center, AREEO, Semnan, Iran)

harsh environments because increasing in tillering exactly causes increasing in dry matter per water consumption units in the water productivity equation (OGTR 2017; Pacific Seeds 2008).

Temporary dormancy is one of the most important reactions of sorghum against strong and prolonged water stress in sorghum, which is the leaves of sorghum roll inwards and after drought the plants resume growth (OGTR 2017).

Accumulation of silica in the cell wall caused tolerance against abiotic and even biotic stress such as drought and salinity. There is a level of silica in the endoderm of root cell wall of sorghum that keeps root cells alive and healthy under drought stress and this is a feature to increasing water productivity (Santi et al. 2018).

17.5 Evaluation of Water and Energy Productivity in Sorghum and Corn Forage

To evaluate water and energy productivity in sorghum and corn, an experiment was carried out in Zayandeh Rud River Basin—Roodasht area. The study was conducted in hot and dry regions of Iran located in Isfahan province with altitude of 1570 m and average annual rainfall of 90 mm.

17.5.1 Materials and Methods

To assessment and comparison of water and energy productivity of sorghum and corn under different levels of irrigation water an study was conducted in Zayandehrud River Basin during 2016–2017. Tape irrigation is one of the drip irrigation systems, which is water flows in perforated narrow pipes, where a strip around plant gets wet by drips. During the experiment in summer, there is no effective rainfall and temperatures are high, which is reaching an average of 35 °C in July. A split plot experimental design was setup with three water levels including 60, 80 and 100% of crop water requirement (ETc), two maize cultivars (704 & Maxima) and two sorghum cultivars (Pegah & Speed feed) with three replications. This required a total of nine plots (three treatments with three replications), with each plot measuring 8 m in width and 30 m in length (along the crop rows). Each plot consisted of nine crop rows with a plant row spacing of 70 cm. The soil infiltration rate was moderate and the soil bulk density till depth 60 cm was 1.25 g/cm^3. The EC and pH of irrigation water were 4.2 dS/m and 7.2, respectively. The soil water content in the root zone was recorded throughout the season. Due to the fact that the flow of water in the Zayandrud River is not permanent, water resources used in crop production in the study area depend on groundwater resources, while groundwater resources are highly dependent on the flow of water in the river. The different levels of irrigation water were applied volumetric basis using a drip irrigation system based on 5–7 days irrigation intervals in accordance with water requirement calculation. Then the volume of water required for each treatment, considering an irrigation efficiency equal to 90%, was calculated based on the area cultivated and depth of water. The ETo was accounted with the use of ETo calculator (Version 5, Raes et al. 2012). For the calculation of evapotranspiration, the ETo calculator uses Penman–Monteith equation. The inputs required for the model are: [maximum air temperature (Tmax), minimum air temperature (Tmin), maximum relative humidity (RHmax), minimum relative humidity (RHmin), sunshine hours (n/N), and wind speed at a height of 2 m (u2) (Salemi et al. 2011). Long-term weather data (1979–2015)] were collected at Zayandehrud River Basin and in this study, the Penman–Monteith model was used for ETo calculation. This method is the most general and widely used model for calculating daily reference ETo and is recommended by FAO (Allen et al. 1998). In the study area, the highest ETo of 13.9 mm/day was obtained in the

Fig. 17.2 View of the experiment in various stages of growth (photo taken by authors)

summer. Sampling and harvesting time were performed based on the phonological stages of sorghum and corn in the seed dough stage. So that in the dough stage, the fresh yield of the forage was determined in the field, and from every plot one sample of fresh forage was transferred to the laboratory for measuring the amount of dry matter. To measure the fresh and dry yield whole biomass on the ground surface was harvested, and to determine the qualitative traits and silage feasibility the harvested forage was a silo. Based on yield and water consuming the amount of water and energy productivity was determined. The concept of water productivity that uses in the experiment was biomass/m^3 or kg of fresh forage per m^3 because in forage production whatever is important is biomass production (Fig. 17.2).

17.5.2 Results

In order to determine the effects of crop type in the study, the obtained data were analyzed using compound variance analysis and the average of different treatment were compared in 5% probability level using Duncan statistical method. The results in Tables 17.2, 17.3, and 17.4 are summarized as follows:

Table 17.2 Comparison of the amount of fresh forage, dry forage, water, and energy productivity in sorghum and maize under average of different levels of irrigation in Zayandeh Rud River Basin during 2016–2017

	Maize	Sorghum
Fresh forage (ton/ha)	55.96	91.9
Dry forage (ton/ha)	17.36	26.36
Energy productivity (Kg/MJ) dry forage	0.57	1.12
Water productivity (kg/m^3) for dry forage	2.99	5.1

Table 17.3 Comparison of the amount of fresh forage, dry forage, water, and energy productivity in various cultivars of sorghum and maize under average of different levels irrigation in Zayandeh Rud River Basin during 2016–2017

	Maize cultivars		Sorghum cultivars	
	704	Maxima	Pegah	Speed feed
Fresh forage (ton/ha)	61.23	50.68	103.84	79.96
Dry forage (ton/ha)	18.91	16.16	30.32	26.26
Energy productivity (Kg/MJ) dry forage	0.62	0.52	1.26	0.98
Water productivity (kg/m^3) for dry forage	2.76	3.21	5.44	4.64

Table 17.4 Comparison of the amount of fresh forage, dry forage, water and energy productivity in various cultivars of sorghum and maize under different levels of irrigation in Zayandeh Rud River Basin during 2016–2017

	Maize			Sorghum		
60% Irrigation	100% Irrigation	80% Irrigation	60% Irrigation	100% Irrigation	80%	Irrigation
Energy productivity (Kg/MJ)	0.7	0.53	0.48	1.15	1.09	1.11
Water productivity (kg/m^3) dry forage	3.55	2.75	2.66	4.75	4.63	5.76
Water productivity (kg/m^3) fresh forage	11.3	9.06	9.08	16.7	16.91	19.5

- There are significant differences (at 1% level) between sorghum, corn, and their cultivars in terms of fresh and dry forage.
- Different levels of irrigation water have a significant difference in the amount of dry and fresh fodder in both sorghum and maize.
- The water productivity was affected by interaction between irrigation water levels and crop types significantly.
- In all irrigation water levels of sorghum, the water productivity and energy productivity were superior to corn, which is referred to as less water consuming and more forage yield in sorghum compared to corn.

17.5.3 Conclusion

It concluded that the negative effect of water stress on the amount of forage production in sorghum varieties is lower than maize varieties. Sorghum cultivars in terms of both forage yield and water productivity are superior to maize cultivars, and in terms of energy productivity they are superior to maize cultivars. In confirmation of obtained results, Howell et al. (2008) demonstrated that sorghum compared to corn able to attain high water productivity with less evapotranspiration and water requirement, where the required water was obtained during the growing season for forage sorghum 489 mm and water productivity of 3.5 kg/m^3. Adams and Erickson (2016) indicated that sorghum was able to maintain yield under water stress (50 and 75% water input of the control), which leads to improving water productivity. As a management strategy in the field, implementation of deficit irrigation during the growing season will depend on environmental conditions such as air temperature and humidity. In dry regions where agriculture relies on irrigation, in conditions of high evapotranspiration and in loamy textured soils, this strategy may be viable for improving forage yield, water, and energy productivity in the field. It seems that change in crop rotation and cultivation stresses tolerant forages in Zayandeh Rud River Basin, will provide a considerable water saving and sustainability in agroecosystems due to more elevating water and energy productivity.

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