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Water management in Iran: what is causing the looming crisis?

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Abstract Despite having a more advanced water management system than most Middle Eastern countries, similar to the other countries in the region, Iran is experiencing a serious water crisis. The government blames the current crisis on the changing climate, frequent droughts, and international sanctions, believing that water shortages are periodic. However, the dramatic water security issues of Iran are rooted in decades of disintegrated planning and managerial myopia. Iran has suffered from a symptom-based management paradigm, which mainly focuses on curing the problem symptoms rather than addressing the main causes. This paper reviews the current status of water resources in Iran and recognizes three major causes for the current water crisis: (1) rapid population growth and inappropriate spatial population distribution; (2) inefficient agriculture sector; and (3) mismanagement and thirst for development. The country is faced with serious challenges in the water sector, including but not limited to rising water demand and shortage, declining groundwater levels, deteriorating water quality, and increasing ecosystem losses. If immediate actions are not taken to address these issues, the situation could become more tragic in the near future. The paper suggests some crisis exit strategies that need to be immediately adopted to secure sustainable water resources, if Iran does not want to lose its international reputation for significant success in water resources management over thousands of years in an arid area of the world.

Keywords Water resources · Management · Water Security · Agriculture · Population · Development · Iran · Middle East

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Introduction

Located in West Asia, bordering the Caspian Sea in the north, and the Persian Gulf and Sea of Oman in the south, Iran is the second largest country in the Middle East (after Saudi Arabia) and the 18th largest country in the world with an area of 1,648,195 km^2. Iran has 5,440 km of land borders and 2,440 km of water borders with its neighbors: Afghanistan and Pakistan in the east; Turkmenistan, Azerbaijan, and Armenia in the north; Turkey and Iraq in the west; and the Arab States of the Persian Gulf in the south. With an estimated population of over 77 million, Iran is the second most populated country in the Middle East (after Egypt) and the 17th most populated country in the world.

Iran has a diverse topography. The lowest point in the country is on the southern coast of the Caspian Sea (28 m below sea level) and the highest point is Mount Damavand (5,671 m above sea level (m a.s.l.)), not very far from the Caspian Sea coast. The mean altitude is 1,200 m a.s.l., most of the country is above 450 m a.s.l., and one-sixth of it is over 2,000 m a.s.l. About 90 % of Iran's land area falls within the Iranian Plateau. One-fourth of the country comprises deserts and almost one-fourth of it is arable. The rest is worn to mountains and highlands.

Iran enjoys a large climatic variability, mainly affected by the subtropical high-pressure belt. Temperatures can vary significantly (from −20 to +50 °C) throughout the country and during the year. January, with an average temperature range of −6 to 21 °C, and July, with an average temperature range of 19 to 39 °C are, respectively, the coldest and hottest months of the year in most of the country. The annual precipitation is 413 billion cubic meters (bcm), but it varies greatly across the country, ranging from less than 50 mm in central Iran to about 1,000 mm in the Caspian coast. Average precipitation is about 250 mm per year, less than one-third of the average annual precipitation at the global level. Most of the country receives less than 100 mm of precipitation per year, and 75 % of the country's precipitation falls over only 25 % of the country's area. Also, 75 % of the precipitation is off-season, i.e., falls when not needed by the agricultural sector. Winter is the season with the heaviest precipitation and only few parts of the country (Caspian Sea coast, northwest, and southeast) receive rainfall in summer. The considerable spatial and temporal precipitation variability in Iran has been the main motivation to construct numerous dams and large reservoirs to regulate water flows.

Most (65 %) of the country is considered to be arid, 20 % is semi-arid, and the rest has a humid or semi-humid climate. There are several large rivers throughout the country. Only one river is navigable, and the others are too steep and irregular. Streams are seasonal and variable. They normally flood in spring (with the ability to create some damage), but have little or no water in summer. The total renewable freshwater of the country and the total returned water from consumption are respectively estimated at 130 and 29 bcm annually. The annual renewable water per capita in Iran is estimated to be less than 1,700 m^3, well below the global level (7,000 m^3) and slightly above the MENA (Middle-East and North Africa) level (1,300 m^3).

This paper provides an overview of the current status of water resources in Iran. It is argued that Iran is experiencing significant water challenges that have turned water security to a national priority at the moment. The next section discusses different aspects of the water crisis; "The crisis drivers" section identifies the major causes of the crisis; and the last section concludes with recommending effective strategies for addressing the crisis and improving water security in Iran.

The looming water crisis

Drying lakes and rivers, declining groundwater resources, land subsidence, water contamination, water supply rationing and disruptions, forced migration, agricultural losses, salt and sand storms, and ecosystem damages are the modern water-related issues of a nation which was once recognized as the pioneer of sustainable water management for thousands of years. There is no doubt that the ancient Persians proved their determination to survive and thrive by developing innovative methods for regulating, withdrawing, transferring, redirecting, and distributing water in an arid area of the world where water availability is seasonal. The Persians are still proud of their significant contributions to hydraulic engineering by inventing qanat—a series of well-like vertical shafts, connected by hand-dug underground tunnels—for sustainable groundwater withdrawal and transfer (Ahmadi et al. 2010; Beaumont 1971; Fisher 1928; Jomehpour 2009; Wulff 1968) centuries before the Romans built their aqueducts; they developed one of the oldest water regulation, monitoring, and market systems in the history; and they constructed the tallest historic arch dam of the world, large gravity dams, flood control infrastructure, weirs, water transfer and delivery channels, as well as water mills long before most other nations. In the modern times, however, rapid socioeconomic development has created a serious water crisis for this proud nation.

In the west of the country, Lake Urmia—the largest lake in the Middle East and one of the world's largest hypersaline lakes—has significantly shrunk as a result of frequent droughts and aggressive upstream water use, diversion, and storage (Fathian et al. 2014; Khatami 2013; Norouzi et al. 2013; Sima and Tajrishy 2013). Shrinkage of the lake and constriction of a controversial causeway over the lake have had significant implications for the lake's valuable ecosystem and the regional economy (Eimanifar and Mohebbi 2007; Hassanzadeh et al. 2012; Mohebbi et al. 2011; Zeinoddini et al. 2009, 2014). The resulting salt storms (Abbaspour et al. 2012; Garousi et al. 2013) from the lakebed are expected to destroy the surrounding farmlands by depositing the lakebed material, and to have tragic health effects, with the potential to force out-migration.

In the east, Lake Hamun is disappearing as a result of the ever-lasting transboundary conflict with Afghanistan over the Hirmand (Helmand) River (Ettehad 2010; Madani 2010a; Madani and Hipel 2011; Najafi and Vatanfada 2011) as well as water mismanagement in the Iranian portion of the watershed. Lack of water and frequent dust storms (Gerivani et al. 2011; Sharifikia 2013) have forced migration and devastation of some small villages in the area.

In the center, Zayandeh-Rud River—the backbone of human development in central Iran—dries up seasonally, imposing extensive pressure on the agriculture, industries, and urban populations (Madani Larijani 2005b). Not only have the extensive water transfer policies to sustain the Zayandeh-Rud River been ineffective, but they are also the cause of growing demand and further water shortages in the region (Gohari et al. 2013b; Madani and Mariño 2009). There is almost no hope in the recovery of the Gavkhouni wetland and its valuable ecosystem at the end of the river, which has always been the loser of the unfair competition over Zayandeh-Rud's water (Gohari et al. 2014).

Urmia, Hamoun, and Gavkhouni are not the only drying water bodies. Parishan (Ghazali 2012) and Shadegan (Hoor-Al-Azim) (Davtalab et al. 2014; Kaffashi et al. 2011; Sima and Tajrishy 2006; Zamani-Ahmadmahmoodi et al. 2010) are the other sister lakes and wetlands which have lost their health due to the anthropogenic effects of short-sighted development projects and the low value of ecosystem service benefits in the regulators' view. This is despite the fact that Iran has been committed to preserve these water bodies under the well-known Ramsar Convention of 1971 that recognizes the wetlands' fundamental ecological functions as well as their economic, cultural, recreational, and scientific values. Ironically, the country whose name is associated with the famous "Convention on Wetlands of International Importance" is at the forefront of damaging its valuable wetlands for the sake of economic development.

Similar to the enclosed water bodies, rivers have been the victims of aggressive human developments for enhancing regional economies. As one of the main products of the Iranians' hydraulic mission, dams are built one after another to store water in reservoirs in order to support agricultural activities, increase power generation, and secure urban water supplies. Iran ranks third in the world with respect to the number of dams it has under construction. Currently, the country has 316 small and large dams, providing a storage capacity of 43 bcm and has 132 dams under construction. In addition, Iran is exploring the feasibility of constructing 340 new dams. However, the outcomes of this notable record for a country that has been able to sustain development under serious international sanctions are tragic. Different experiences of serious ecosystem damages, water quality degradation, inundation of historic sites, land use changes, water seepage, and increased downstream development under the perception of increased water availability (AnvariFar et al. 2013; Gohari et al. 2013b; Karimi et al. 2007; Kerachian and Karamouz 2006; Manouchehri and Mahmoodian 2002; Mohammadi et al. 2007; Tajziehchi et al. 2013) make the Iranian dam construction pride questionable.

The Iranian water tragedy is not limited to surface waters. Iran is currently among the top groundwater miners in the world (Döll et al. 2014; Gleeson et al. 2012). It is estimated that the Iranians have already used most of their groundwater reserves. The government has limited control over groundwater abstraction. Energy and water are highly subsidized, leaving no incentives for farmers to increase the efficiency of water use. The only limiting factors for groundwater withdrawal are the well depth and pumping capacity. Once the groundwater table drops, farmers dig deeper and install larger pumps (Foltz 2002). The groundwater situation has been reported to be extremely critical in some parts of the country (Bagheri and Hosseini 2011; Hojjati and Boustani 2010; Izady et al. 2012; Soltani and Saboohi 2009). The traditional sustainable groundwater withdrawal through qanats is no longer feasible. Similar to many springs, most qanats have dried up, losing the hydraulic head battle to deep wells. The latter became popular following the introduction of western groundwater pumping technologies and the socioeconomic changes resulting from the land reforms in the White Revolution of the Shah of Iran in 1963 (Madani 2008) to abolish feudalism by transferring land ownership from influential feudal landlords to peasants who represented 40 % of Iran's population at the time. Declining groundwater tables have also caused significant land subsidence throughout the country (Dehghani et al. 2009, 2013; Motagh et al. 2007; Mousavi et al. 2001). With the annual land subsidence of 36 cm, it is said that the Tehran Plain is currently experiencing more land subsidence than anywhere else in the world.

Most Iranians have access to improved drinking water sources and sanitation facilities both in urban and rural areas (Cech 2010; Madani Larijani 2005a). Due to high water treatment and quality standards, the quality of Iran's domestic water supply has been generally good and significantly better than the other countries in the region. However, concerns about the quality of tap water in urban areas are increasing due to wide agricultural activities near urban areas as well as lack of an appropriate sewage collection and treatment system, which allows for gradual discharge of domestic wastewater into groundwater. Studies show alarming levels of nitrate in different parts of the country, especially in Tehran (Esmaeili et al. 2014; Farhadinejad et al. 2014; Imandel et al. 2000; Jalali 2005; Joekar-Niasar and Ataie-Ashtiani 2009; Latif et al. 2005; Razmkhah et al. 2010). In some regions, people have lost their faith in tap water quality and have turned to bottled water, even though bottled water is not seriously regulated in Iran (Fattahi et al. 2013; Jahed Khaniki et al. 2010; Samadi et al. 2009). In addition to water quality problems, water supply rationing and disruptions have been experienced and are becoming more common in the capital and other major metropolitan areas, during hot summer months of dry and even normal years (Foltz 2002; Janparvar and Nairizi 2007; Vojdani 2004). With old water distribution networks, water losses in these major cities can exceed 30 % while interest still remains in finding new supply sources rather than retrofitting the old systems to minimize network losses.

Limited water and increasing demand have created new water security issues and increased tension over transboundary water systems both regionally and internationally. Inside the country, conflicts continue between provinces over transboundary water systems such as Urmia (Madani and Zarezadeh 2014; Najafi et al. 2013; Oloumi Zad et al. 2013), Karkheh (Roozbahani et al. 2011), Ghezel-Ozan (Zarezadeh et al. 2013), and Zayandeh-Rud (Madani 2007). These conflicts have been intensified through the reforms by the President Ahmadinejad's administration, which changed the water management boundaries from the ideal watershed boundaries to the provincial boundaries to empower the provinces (Zarezadeh et al. 2013). These reforms have simply increased the number of stakeholders and promoted the "tragedy of the commons" (Hardin 1968) in different watersheds.

At the international level, conflicts continue over sharing the surface waters. Examples include the conflict over the Hirmand River with Afghanistan in the east (Ettehad 2010; Najafi and Vatanfada 2011) and over the ownership of the Caspian Sea—the world's largest enclosed body of water, the source of more than 90 % of the world's sturgeon, and a major source of oil and gas in the near future—in the north

(Madani et al. 2014b; Mianabadi et al. 2014; Sheikhmohammady and Madani 2008a). Failure in reaching an agreement over sharing the Caspian Sea with Azerbaijan, Kazakhstan, Russia, and Turkmenistan since the collapse of the Soviet Union (Madani et al. 2014a; Sheikhmohammady and Madani 2008b) has resulted in an international tragedy of the commons, associated with high level of water pollution and ecosystem damages (Behmanesh et al. 2013; Read et al. 2014; Sheikhmohammady and Madani 2008b). The situation is less tragic in other transboundary surface water systems in which Iran has better access to upstream water sources such as the Tigris-Euphrates system, shared with Turkey, Iraq, and Syria; and Aras system, shared with Armenia, Azerbaijan, and Turkey. However, Iran's attempts to increase its use of outgoing surface flows can increase the international tensions with the neighbors in the future. Similarly, Iran's aggressive groundwater withdrawal can create some conflicts in the years to come in the case of transboundary aquifers, including the Sarakhs aquifer, shared with Turkmenistan; the Lenkoran/Astara aquifer, shared with Azerbaijan; the Nakhichevan/Larijan and Djebrail aquifer, shared with Armenia, Azerbaijan, Georgia, Russia, and Turkey; and the Leninak-Shiraks aquifer, shared with Armenia, Azerbaijan, and Turkey.

The current water problems of Iran cannot be fully blamed on the Iranians. Iran is one of the world's most disaster-prone countries. During the last two decades of the 20th century, 11 million Iranians per year were exposed to floods with an average death toll of 131 people per year (DOE 2010). Drought are also common and have become more frequent in Iran (Bari Abarghouei et al. 2011; Golian et al. 2014; Morid et al. 2006; Nikbakht et al. 2013; Raziei et al. 2009), having significant impacts on agriculture, urban water supply reliability, ecosystem, and rural communities (Abbaspour and Sabetraftar 2005; Ardakanian 2005; Delju et al. 2013; Jahani and Reyhani 2007; Janparvar and Nairizi 2007; Keshavarz et al. 2013; Mousavi 2005; Salami et al. 2009). Furthermore, based on the majority of projections, climate change is expected to exert extra pressure on Iran's water resources by making the region hotter and drier (Abbaspour et al. 2009; Evans 2009; Jamali et al. 2012; Zarghami et al. 2011), having major implications for agricultural production (Gohari et al. 2013a; Moradi et al. 2013), hydroelectricity generation (Davtalabsabet et al. 2013; Jamali et al. 2013), and reliability of water supply and reservoir operations (Ashofteh et al. 2013; Davtalab et al. 2014; Gohari et al. In Press).

In addition to the climatic stressors, in the last decades, Iran has not had a stable economy under the serious international pressure through major economic sanctions. Generally, economic insecurity and high inflation rates encourage short-term benefit maximizing attitude and non-cooperative behavior in water management (Madani and Dinar 2012b), and Iran has not been an exception. Both users and decision makers have been more interested in increasing immediate benefits. So, in the absence of serious effective exogenous regulatory institutions (Madani and Dinar 2013) and economic incentives for users' cooperation (Madani and Dinar 2012a), the status of the country's water resources has deteriorated over time.

In practice, the separation of "development" from "environment" (Hjorth and Madani 2013) and aggressive short-sighted regional development plans have resulted in unintended hydro-environmental problems whose long-term costs are significantly higher than their short-term benefits. No matter how advanced the Iranian water management system is in comparison with the other countries in the Middle East, the reviewed evidences leave no doubt that Iran is currently experiencing a serious water crisis. But, this observation is not new. Academics and practitioners have continuously expressed their concern and warned about the looming water crisis (Foltz 2002; Karbalaee 2010; Madani 2003; Madani Larijani 2005a; Motiee et al. 2001; Yazdanpanah et al. 2013a, b), with no success in promoting any serious action by the government.

In theory, Iran is currently experiencing the growth and underinvestment problems (Mirchi et al. 2012, 2014) that the West experienced in the 20th century or is experiencing today, e.g., the ecological problems of the Great Lakes (Breffle et al. 2013; Danz et al. 2005; Mirchi and Watkins 2013) and the Everglades (Belanger et al. 1989; Finkl 1995; Graf 2013), California's Sacramento-San Joaquin Delta crisis (Lund et al. 2010; Madani and Lund 2012; Madani and Lund 2011; Tanaka et al. 2011), the Ogallala aquifer's overexploitation tragedy (Sophocleous 2010; Verchick 1999; Wohlers et al. 2014), vulnerability of developed floodplains (Burby 2006; Elledge and Madani 2012; Lugeri et al. 2006, 2010; Madani et al. 2007), pollution of the River Rhine (Plum and Schulte-Wülwer-Leidig 2014; van Dijk et al. 1995; Wieriks and Schulte-Wülwer-Leidig 1997), and over-damming of the Klamath (Gosnell and Kelly 2010; Hamilton et al. 2005; Powers et al. 2005) and Columbia rivers (Harnish et al. 2014; Kareiva et al. 2000; Raymond 1988). These problems are normally the products of rapid investment and growth in one sector without considering the dynamic relationships of the growing sector (e.g., economy, agriculture, and infrastructure) with the other sectors (e.g., water, environment, and ecosystem) (Madani 2010b; Mirchi et al. 2010) in the absence of an integrated view of the complex human-natural system of systems (Hjorth and Madani 2014). As a result, growth in one sector has caused secondary negative impacts on the other sectors (e.g., ecosystem losses) and a long-term negative feedback or impact on the original sector (e.g., forced migration due to increased water and air pollution). If timely regulatory actions are not taken in these cases, the unintended damages can become fully irreversible.

What makes the current problems in Iran different from similar problems in the West is the depth and extent of the secondary impacts of development. Rather than proactive management to prevent water problems, Iran's reactive management has focused on curing the symptoms, while the causes of the problems are becoming worse over time. If development is to be sustainable, Iranians need to replace symptom management with problem prevention. This would not happen in the absence of a clear understanding of the problem production mechanisms and the key problem drivers.

This paper tries to identify the main causes of the water crisis in Iran and provide some exit strategies with the hope in the improvement of the current situation. The paper should also be considered as a call for action by the Iranian decision makers to make fundamental changes to the current water management practices and institutions, and as a call for research by the water practitioners to further investigate the problem drivers and provide practical solutions.

The crisis drivers

The current water crisis in Iran has three major drivers (Madani 2014):

Population growth and distribution

Iran has experienced a significant population increase in the past century. Estimates suggest that the Iran's population remained below 10 million people throughout the 19th century (Seyf 2009). By the time of the Islamic Revolution of 1979, Iran's population had passed 35 million due to the significant socioeconomic development of the country in the 20th century. After the Revolution, Iran's population almost doubled within the last two decades of the 20th century. More than half of the current population of 77 million are under 35 years old, reflecting the dramatic population increase after the Islamic Revolution, which promoted different socioeconomic, cultural and ideological changes in Iran. With the support of the government, the population growth rate exceeded 4 % during the Iran-Iraq war in the early 1980's. The result of this baby boom is a generation that accounts for 70 % of unemployment and is ironically blamed by the government for lowering the current fertility level, which has brought down the population growth rate to 1.3 %.

The dramatic population increase in Iran has reduced per capita renewable freshwater availability. Nevertheless, Iranians continue to use more than 250 l of water per day per person and their daily consumption can exceed 400 l per person in some urban areas like Tehran. This means that Iran's water usage is twice the world's standard despite its limited water availability. To satisfy their high water demand, Iranians are currently using more than 70 % of their renewable freshwater resources, while using more than 40 % of renewable freshwater resources means entering the water stress mode.

In addition to a sudden population growth, an inappropriate population distribution is challenging the Iranian water managers. Generally, water development has played a major role in the development of human settlements in the country (Seyf 2009). Most Iranians have preferred to live in regions with better water availability. About 50 % of the country's population lives in the northern and western regions, which hold over 70 % of the country's water resources (Madani Larijani 2005a). Nevertheless, there remains a mismatch between the water delivery capacity and regional water demand in most parts of the country. The urban portion of the population is currently about 70 %, much higher than 27 % in the 1950's and 44 % in the 1970's, as a result of rapid urbanization and increased migration from rural areas to urban areas for better living conditions. Eight Iranian cities have a population of greater than 1 million and 76 cities have a population of greater than 100,000 people. The population in the metropolitan Tehran has surpassed 14 million (18 % of the country's population), despite its limited access to water resources.

The inappropriate spatial distribution of population and high population concentrations in some areas have resulted in the implementation of major water transfer projects which can periodically solve water shortage issues without addressing the main cause of the water shortage (i.e., population growth). Gohari et al. (2013b) refer to water transfer as "a fix that backfires", arguing that major water transfers to the Zayandeh-Rud river basin and the Isfahan Province have resulted in the promotion of development and population increase due to the perception of water availability. Therefore, water transfers have become the cause of further water shortage problems in the basin although they had the ability to cure the symptom (water shortage) periodically.

To have sustainable water resources, Iran needs to control the population growth and distribution. While Iran might have the capacity of holding a larger population, increased population growth can have catastrophic effects, if spatially uncontrolled. The uneven geographic distribution of welfare and better living conditions in cities attract people to particular urban areas within the country, exacting extra pressure on water resources and creating a competition between urban and rural areas over the limited water resources. Normally, urban areas are the winners of such competitions, resulting in increased water allocations to these areas, which in turn promotes development and population growth. The "success to the successful" dynamics continue and urban areas keep growing, asking for more water, which can only be satisfied through water transfer infrastructure due to the unavailability of local resources.

Despite the fact that the population is one of the main causes of Iran's water crisis, the government of Iran is now showing a strong interest in boosting the population. This interest is rooted in concerns about the future age distribution projections. The government is reverting the earlier birth control policies, which had been set to address the high population growth in the 1980's. Just recently, the Iranian Parliament passed a new law that makes sterilization and vasectomies illegal. This law is just one example of the new policies that clearly indicate the government's serious determination to increase the fertility level. The turn in the population growth policies is really striking and reflects the confusion about the socioeconomic effects of population growth among the Iranian decision makers. What is clear though is that Iran definitely lacks the required water resources and infrastructure to satisfy the increased water demand. Without strong population distribution adjustment and water consumption reduction measures, the new population growth policies can only have catastrophic effects.

Inefficient agriculture

Iran has always suffered from a seriously inefficient agriculture (Katouzian 1978; Nattagh 1986) that heavily relies on irrigation (Lambton 1938; Fitt 1953; Seyf 2006) and consumes most of the country's limited water resources. While only 15 % of the country's area is cultivated, this sector is responsible for 92 % of the water consumption in Iran (compared to the 7 % domestic water use and 1 % industrial water use). Since the Islamic Revolution, the government has tried to be supportive of this sector in order to achieve food security and increase the non-oil production revenues. This policy was of particular importance and turned to be helpful during the Iran-Iraq war. Nevertheless, the economic efficiency of this sector has decreased significantly over time. Currently, this sector only provides 23 % of the jobs, and its contribution to GDP has decreased from over 33 % to 13 %, while Iran has also lost its leading position at the international level in export of some high-value agricultural products like pistachio.

To support this sector, the government has heavily subsidized agricultural water and energy use. The significantly cheap prices have not provided any motivation for increasing the production efficiency in this sector. The average irrigation efficiency is less than 35 %, and only 5 % of the farmed area is under pressured irrigation. The rainfed agriculture is also unproductive, mainly due to the rainfall patterns. While the area under rainfed and irrigated agriculture are almost equal, the share of rainfed agriculture from the total yield is only about 15 % (compared to the global food production shares of the rainfed and irrigated agriculture, which are 60 and 40 %, respectively). The crop pattern does not match the regional water availability conditions and has remained more responsive to the traditional crop choices and farming practices as well as the guaranteed crop purchase prices set by the government.

Due to the unavailability of sufficient surface water, the agricultural sector also consumes a lot of groundwater, which currently satisfies 55 % of the total water demand in Iran. The agricultural sector is responsible for more than 90 % of the groundwater consumption (compared to the 8 % domestic groundwater use and 2 % industrial groundwater use). The excess groundwater withdrawal is hard to estimate, but the dramatic drop of groundwater table (2 m per year in some parts of the country) reflects the extent of the consumption of the non-renewable portion of groundwater. As a result, 277 of the 609 plains in the country are in a critical condition and the declining groundwater table (Forootan et al. 2014; Joodaki et al. 2014) has caused significant land subsidence in many plains throughout the country (Dehghani et al. 2009, 2013; Motagh et al. 2007; Mousavi et al. 2001).

Because of its oil-based economy, Iran has never been seriously concerned about the economic efficiency of the agricultural sector (Katouzian 1978). Without a comprehensive plan for the empowerment of farmers and rural communities, populist actions of the Iranian decision makers, such as substantial subsidization of water and energy, to support farmers have failed to increase welfare in this sector. The economic efficiency of this sector has remained low, leading to low income levels. The rural population have no serious job alternative other than farming (Nattagh 1986) if they want to stay in rural areas. Therefore, farmers have a tendency to leave farming and migrate to urban areas which have been favored more by the government (Katouzian 1978) and provide better living conditions.

In agricultural zones in the vicinity of urban areas, the high land values due to rapid urbanization is the main motivation for the farmers to quit farming by selling their lands and switching to better-paid jobs. Those farmers who stay in business must continuously deepen their wells to withdraw groundwater from the declining aquifers, while the water and energy prices are not high enough to be prohibitive. Therefore, farmers continue to contribute to groundwater mining and the declining energy use efficiency in the agricultural sector (Beheshti Tabar et al. 2010). On the other hand, due to the non-linear relationship between groundwater levels and energy use for groundwater pumping (Moazedi et al. 2011), the government has to exponentially increase its subsidies over time as the groundwater tables drops. To prevent further economic and water losses, the government has slightly raised energy prices in recent years. Also, in different parts of the country, smart groundwater monitoring devices (Moazedi et al. 2011; Zekri 2009) have been installed with the potential for real-time control of energy and water use. Nevertheless, the effectiveness of these actions are yet unknown. What is known is that the continuation of the current water use trends in the agricultural sector will exacerbate the water crisis. Iran seriously needs its agriculture to be modernized/industrialized and become economically efficient.

Mismanagement and thirst for development

More than anything, the water crisis in Iran is the result of decades of bad management. Iran has gone through significant socioeconomic and political changes in the last century. While the desire for rapid modernization during the Pahlavi Dynasty had major socioeconomic benefits, the modernization process was not free of effects on the country's invaluable natural resources. The Islamic Revolution and the international pressure on Iran further strengthened the thirst for development and the desire to prove independence to the world. The Iranians were more successful than most nations of the developing world in maintaining their independence in the realm of policy-making (Foltz 2002) and in relying on national expertise under major sanctions by the West. However, rapid development and construction of major infrastructure with minimal concern for their long-term non-economic impacts have created major water and environmental problems that call this success into question.

It is undeniable that the international sanctions have slowed down the development process in Iran by limiting the Iranians' access to new technologies. But, Iran's water problems are not due to a lack of access to technology or technical expertise as some decision makers claim. Indeed, Iran is suffering from disintegrated decision making and problem solving by knowledgeable experts who act independently. One major cause of such disintegration is the water governance structure, which involves too many stakeholders and an undesirable hierarchy in water resources management. Competition and conflicts increase with the number of stakeholders. In addition, an increased level of hierarchy is associated with opportunities for corruption, which makes the Iranian water management system more inefficient. The situation has been exacerbated by the structural reforms of President Ahmadinejad that changed the water management boundaries from watershed boundaries to political (provincial) boundaries, creating competitions among the provinces to maximize their immediate gains from the shared water systems (Zarezadeh et al. 2013) resulting long-term losses for all parties.

The thirst for development motivates "nature control" rather than "nature management". Interest in the latter requires appreciating the fact that humans' ability to put nature under control for maximizing economic benefits is limited (Madani et al. 2007). Overlooking the important linkage between "development" and "environment" in coupled human-natural systems (Hjorth and Madani 2013) results in development projects that seriously affect the long-term welfare of both human and natural systems. Similar to other countries in the Middle East, the thirst for development in Iran has caused a serious managerial myopia. The focus is on rapid development to obtain immediate economic benefits. Given the existing political instability and insecurity within the system, decision makers are more interested in populist development actions which produce immediate economic impacts. For example, the representative of a region in the parliament can pressure the water authorities to finance a dam construction project to help the farmers in his region. If the project is successful, it can boost the regional economy alongside the legitimation of the representative. Locals would then be willing to support the same person and send him to the parliament in the next round. The long-term environmental impacts are not associated with immediate economic benefits and political popularity. Thus, ecosystem preservation remains overlooked when pursuing populist development agendas. Similar development initiatives by other elected officials in the shared river basin will eventually create significant externalities, resulting in long-term losses for all parties. A good example of this situation is the Lake Urmia tragedy, which is perhaps the most catastrophic water problem, experienced by the Iranians to date. The lake has almost dried up because of the anthropogenic effects of selfish and uncoordinated upstream development activities by three provinces in a competitive environment (Khatami and Berndtsson 2013; Norouzi et al. 2013).

Disintegrated management is not limited to the authorities within the water sector. The other causes of the water crisis discussed above (population growth and inefficient agriculture) reflect the lack of coordination among different government sectors. While the country is suffering from an acute water crisis, other authorities within the government are pursuing serious population growth and are trying to 'protect' farmers against water allocation policies that reduce the agricultural water share for the sake of the environment. Similarly, plans for land use, urbanization, food security, transportation, public health, and energy security are independently developed by various government sectors without the required coordination, resulting in major externalities that are normally costly to address.

The situation can be partially blamed on the current governance structure and the political instabilities in Iran. But, the main driver of uncoordinated development in Iran as well as the other Middle Eastern countries is the thirst for development, which prevents a comprehensive understanding of the complex interrelated dynamics and feedback relationship between the different sectors. A similar situation has been observed in the developed countries during their peak development phases, as discussed earlier, but those countries could also develop relatively effective mechanisms to cope with and to prevent the emerging hydro-environmental problems in the aftermath of rapid and shortsighted development. In Iran, however, water management relies on a "crisis management paradigm." This means that the decision makers continue development in search of immediate economic benefits, hoping that no serious problem would interrupt their period of administration. If water problems arise, extra effort will be put mainly into curing the problem's symptoms to bring the situation back to semi-normal conditions. Normally, the solutions are not fundamental and the problems will reappear in some form; but, the hope is that they do not reappear any time soon, when the decision makers are still in charge. Within the crisis management paradigm, problem prevention is less of a concern, as it has no transparent short-term benefits that the public would appreciate and reward the decision makers for.

In analyzing water mismanagement in Iran, one should not overlook the effects of some exogenous factors such as climate variability and extreme events (floods, droughts, and heat waves), political tensions and instability (national and international), economic performance and stability (e.g., high inflation and unemployment rates), and international sanctions. The government continuously blames some of these factors, such as climate extremes and international sanctions, as the main causes of the current situation, claiming that problems are periodic. However, these exogenous issues are only crisis catalyzers, not the main cause of the water crisis. A resilient water management system is expected to be capable of coping with periodic external pressure (Hjorth and Madani 2014) such as droughts, sanctions, or political changes. While external pressure can affect the performance of the system, a resilient system can recover and restore itself once the pressure is removed, without a risk of collapse. The current situation in Iran and status of different water systems in the country prove that Iranians have failed to invest sufficiently into developing a resilient water management system.

Exit strategies and concluding remarks

The water problems in Iran are far too many and significant to leave any doubt about the fact that Iran is experiencing a looming water crisis. Immediate mitigation actions are required to address the existing water security problems throughout the country. There are good signs that the new government of Iran recognizes water security as a national priority at the moment and is trying to address some of the more evident water problems immediately. However, most solution strategies are still shortsighted and are mainly focused on problem symptoms as opposed to problem causes. Fundamental changes in the current Iranian water management paradigm are essential to prevent the development of similar problems in the future and to secure sustainable water resources for Iran. More than anything, the Iranian decision makers need to appreciate the complexity of the coupled human-natural systems to be able to develop water management solutions that have no or minimal secondary impacts. It is true that every country in the developing world and Middle East has the right to develop and grow as the developed world did in the past century, but reproducing the secondary environmental problems of development, which have been already experienced in the West, is unnecessary and unwise. There are free opportunities for Iran to learn from the costly failures of water management in the West (especially in the United States and California) to minimize the risk of water resources development plans.

There is an urgent need for revisiting the new population growth policy in Iran. While the current age distribution of Iran's population is undesirable and can have some long-term socioeconomic impacts, the negative consequences of uncontrolled population growth and rapid urbanization can be much more significant. Optimizing the spatial distribution of the current population should be prioritized over improving the age distribution of the population. Major urban areas in Iran are already challenged with satisfying the needs of the existing population. Without major socioeconomic and political reforms to address the current imbalance of power and services throughout the country migration to major metropolitans will continue. So, the new population growth policies will just exacerbate the situation.

The highly inefficient agricultural sector needs fundamental changes to address the current water crisis. Instead of trying to support the farmers to continue business as usual, the government must empower the farmers. The low economic efficiency of farming makes the agricultural sector less attractive. Many farmers keep migrating to the urban areas for better socioeconomic conditions. Those who stay in business have no incentive to change the traditional farming practices and cannot afford adopting new technologies to improve the efficiency of their activities. As a result, this sector continues to degrade in terms of its contribution to the GDP. The current governmental support mechanisms make farmers economically weaker as development continues. Empowerment of the farmers and rural communities can be done by substantial investments in the agricultural sector in order to modernize this sector and make it more economically efficient and attractive. Wealthier farmers will be more innovative and have stronger tendencies to maximize the economic efficiency of farming activities and water use.

Several strategies can be pursued to improve the efficiency of the agricultural sector. First, the inappropriate crop pattern across the country (Faramarzi et al. 2009; Gohari et al. 2013a) should be revised with respect to the macro-level food security priorities as well as regional resource availability conditions. Appropriate crops must be identified for each region based on water/land/energy availability and economic efficiency conditions. Through different economic incentives (e.g., guaranteed purchase of particular crops in specific regions at certain prices), the government can promote crop pattern modifications.

Second, water and energy prices should be raised meaningfully to be reflective of the true cost of water and energy in each region across the country. This, of course, can have serious negative impacts on the socioeconomic conditions of farmers in the short-run and is associated with a high political cost for the government. To prevent such impacts, the government should finance the modernization of agricultural practices that help farmers cut water and energy usage effectively. Although, this strategy requires large initial investments, in the long-term, it is expected to cost less than the current government policy, which heavily subsidizes the increasing water and energy use in the agricultural sector.

Third, the government needs to provide incentives for the formation of regional cooperative agricultural management institutions (e.g., irrigation districts, regional farming authorities, regional farmer co-ops). These entities can increase the economic efficiency of farming by increasing the collective capacity in managing the capital, operation, and maintenance costs of farming as well as controlling crop sale prices at the farm level (which are currently far below the market prices). Around 78 % of the Iranian farmers have farms of less than 10 ha, which in total make up about 37 % of the cultivated land but yield only 10 % of the total agricultural production. On the other hand, the medium-size farms of 10 to 50 ha, which make up for 50 % of the total cultivated area, yield 75 % of the total agricultural production. This simply shows that due to economies of scale and other factors, farming at a scale larger than the current scales can increase the production efficiency.

Fourth, the government must implement an efficient water market. Iranians are recognized for their success in regulation, allocation, and trading water in the ancient times. Modern Iran also requires a reliable water market to increase the economic efficiency of water use. The implementation of a water market requires serious regulation and monitoring of water uses as well as creating a financial mechanism to support water trades. To overcome the current crisis, government should also pursue setting up an environmental water account (Hollinshead and Lund 2006) and try to purchase water from farms with low economic efficiency to recharge aquifers and recover damaged ecosystems.

Water management in Iran should shift its mode from crisis (reactive) management to preventive (proactive) management to prevent serious water problems and ecosystem damages. A proactive management paradigm recognizes the interrelated dynamics of the water sector with the other sectors, cures the problem causes rather than its symptoms, manages water rather than controlling it, and benefits from effective nonstructural (soft) solutions (e.g., regulations, institutions, taxation, monitoring, population control) as much as it benefits from structural (hard or engineering) solutions (e.g., dam construction, water diversion, using irrigation sensors). One of the first steps in improving water management in Iran is the revision of the current water governance structure to remove the unnecessary hierarchies, minimize the number of stakeholders, and empower the Department of Environment (DOE), which is politically weaker than the other government sectors such as the Ministry of Energy (responsible for managing water and power) and the Ministry of Jihad-Agriculture (responsible for managing agriculture). If development is to be sustainable, DOE must have the required authority to enforce environmental regulations, environmental impact assessments, and environmental taxation.

Although tragic, the Lake Urmia disaster can be a turning point in the modern history of water management in Iran. The problem has many serious (including political) dimensions, which have enabled it to receive national attention and to create a consensus between different sectors within the government on the fact that a serious solution strategy must be developed on an urgent basis. The public finds the government responsible and wants its immediate reaction. The significance of this tragedy was such that President Rouhani made promises on solving the Lake's issues in his campaigns before the presidential election. The Urmia Lake problems have made the Iranian media more responsive to the environmental issues and the Iranian society and youth seem to have become more concerned about the hydro-environmental tragedies in different parts of the country. While this level of attention to the Lake Urmia is a good sign, the Iranian decision makers should not forget that this type of problem solving still keeps them in the crisis management mode. In reality, the Lake Urmia disaster is just one evident symptom of the malfunctioning water management system in Iran. There are many other terrifying symptoms that have either already appeared in smaller scales or will appear soon. For example, the hidden groundwater tragedy in Iran might be much more catastrophic in scale and can be the next significant man-made environmental disaster that the Iranian decision makers need to deal with if they continue managing water resources in the reactive mode. Thus, the government must continue its efforts to solve the Urmia Lake problems immediately while also increasing its efforts to prevent other problems through serious revision of the current water management framework.

Citizens, NGOs, and media can play a major role in addressing the current water crisis. While the decision makers must take the main responsibility for the current water status in Iran, the Iranian public must also be blamed for not valuing ecosystem services and not demanding healthy environmental systems from their government. Indeed, like many other developing and even developed societies, the Iranian society does not properly value the ecosystem services and cannot fully comprehend the trade-offs between the immediate economic benefits of rapid shortsighted development plans and their long-term environmental costs. This is due to the lack of knowledge as well as the socioeconomic instabilities of the country in the past decades, making Iranians feel insecure about their future and become more interested in visible immediate benefits rather than the invisible long-term benefits. Environmental activists and NGOs can play a significant role by educating the public about the value of ecosystem services and sustainable development. Social media is a great platform for information sharing and educating the public, especially the Iranian youth. In fact, in recent months, following the outbreak of different news regarding the Lake Urmia tragedy, Iranians have become very active in the social media (such as Facebook, Twitter, YouTube, and blogs). They use the social media for sharing information about the different environmental problems around the country, as well as forming campaigns and signing petitions to respond to various environmental incidents around the country. On the other hand, the Iranian news media which were not previously environmentally active in the past, have become more responsive to the environmental issues, informing the public about the significance of water and environmental problems in Iran, and pressuring the decision makers to take responsible actions in order to address these problems. These activities are very valuable, as eventually, an environmentally educated society will not evaluate and reward the elected officials solely based on their short-term impacts on the economy. Through bottom-up approaches, the Iranian society can force the decision makers to change their behavior, respond to the needs of the society, adopt more pro-environmental development actions, and give more power to regional water management authorities.

Last but not least, it must be noted that while the focus of this paper was on Iran, the problems and solutions discussed are not unique to Iran. Indeed, despite its major deficiencies, the water management system in Iran is much more advanced and successful than most Middle Eastern countries and many other countries in the developing world. Most countries in the region are behind Iran in their development stage. So, they must anticipate experiencing similar or even worse problems in the near future in the absence of serious and timely preventive actions that can be developed based on the costly experiences of the Iranian water sector.

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References

Abbaspour M, Sabetraftar A (2005) Review of cycles and indices of drought and their effect on water resources, ecological, biological, agricultural, social and economical issues in Iran. Int J Environ Stud 62:709–724

Abbaspour KC, Faramarzi M, Ghasemi SS, Yang H (2009) Assessing the impact of climate change on water resources in Iran. Water Resour Res 45(10), W10434. doi:10.1029/2008WR007615

Abbaspour M, Javid AH, Mirbagheri SA, Ahmadi Givi F, Moghimi P (2012) Investigation of lake drying attributed to climate change. Int J Environ Sci Technol 9:257–266. doi:10.1007/s13762-012-0031-0

Ahmadi H, Nazari Samani A, Malekian A (2010) The qanat: a living history in Iran. In: Schneier-Madanes G, Courel M-F (eds) Water and sustainability in arid regions. Springer, Netherlands, pp 125–138. doi:10.1007/978-90-481-2776-4_8

AnvariFar H, Alireza Khyabani HF, Vatandoust S, AnvariFar H, Jahageerdar S (2013) Detection of morphometric differentiation between isolated up- and downstream populations of Siah Mahi (*Capoeta capoeta gracilis*) (Pisces: Cyprinidae) in the Tajan River (Iran). Hydrobiologia 673:41–52

Ardakanian R (2005) Overview of water management in Iran. Water conservation, reuse, and recycling. In: Proceedings of an Iranian-American workshop. The National Academies Press, Washington, DC, pp 18–34

Ashofteh P, Haddad O, Mariño MA (2013) Climate change impact on reservoir performance indexes in agricultural water supply. J Irrig Drain Eng 139:85–97

Bagheri A, Hosseini SA (2011) A system dynamics approach to assess water resources development scheme in the Mashhad plain, Iran, versus sustainability. Proceedings of the 4th International Perspective on Water Resources & the Environment (IPWE), January 2011, Singapore

Bari Abarghouei H, Asadi Zarch M, Dastorani M, Kousari M, Safari Zarch M (2011) The survey of climatic drought trend in Iran. Stoch Env Res Risk A 25:851–863. doi:10.1007/s00477-011-0491-7

Beaumont P (1971) Qanat systems in Iran. Hydrol Sci J 16:39–50

Beheshti Tabar I, Keyhani A, Rafiee S (2010) Energy balance in Iran's agronomy (1990–2006). Renew Sust Energ Rev 14:849–855. doi:10.1016/j.rser.2009.10.024

Behmanesh I, Madani K, Geiger CD, Bahrini A (2013) Stability Analysis of the Proposed Caspian Sea Governance Methods. Proceedings of the 2013 I.E. International Conference on Systems, Man, and Cybernetics (SMC), Manchester, U.K., 1777 – 1782, IEEE, doi:10.1109/SMC.2013.307

Belanger TV, Scheidt DJ, Platko JR (1989) Effects of nutrient enrichment on the Florida everglades. Lake Reserv Manag 5:101–111. doi:10.1080/07438148909354686

Breffle WS, Muralidharan D, Donovan RP, Liu F, Mukherjee A, Jin Y (2013) Socioeconomic evaluation of the impact of natural resource stressors on human-use services in the Great Lakes environment: a Lake Michigan case study. Resour Policy 38:152–161. doi:10.1016/j.resourpol.2012.10.004

Burby RJ (2006) Hurricane Katrina and the paradoxes of government disaster policy: bringing about wise governmental decisions for hazardous areas. Ann Am Acad Polit Soc Sci 604:171–191. doi:10.1177/0002716205284676

Cech TV (2010) Principles of water resources: history, development, management, and policy. John Wiley & Sons

Danz N et al (2005) Environmentally stratified sampling design for the development of Great Lakes environmental indicators. Environ Monit Assess 102:41–65. doi:10.1007/s10661-005-1594-8

Davtalab R, Madani K, Massah A, Farajzadeh M (2014) Evaluating the effects of climate change on water reliability in Iran's Karkheh River Basin. In: Proceedings of the World Environmental and Water Resources Congress 2014. ASCE, Portland, pp 2127–2135. doi:10.1061/9780784413548.212

Davtalabsabet R, Madani K, Massah A, Farajzadeh M (2013) Assessing climate change impacts on water allocation in Karkheh River Basin. American Geophysical Union Fall Meeting 2013, AGU Fall Meeting, San Francisco, California, Abstract #H41K-1411

Dehghani M, Valadan Zoej MJ, Entezam I, Mansourian A, Saatchi S (2009) InSAR monitoring of progressive land subsidence in Neyshabour, Northeast Iran. Geophys J Int 178:47–56. doi:10.1111/j.1365-246X.2009.04135.x

Dehghani M, Valadan Zoej MJ, Hooper A, Hanssen RF, Entezam I, Saatchi S (2013) Hybrid conventional and persistent scatterer SAR interferometry for land subsidence monitoring in the Tehran Basin, Iran. ISPRS J Photogramm Remote Sens 79:157–170. doi:10.1016/j.isprsjprs.2013.02.012

Delju AH, Ceylan A, Piguet E, Rebetez M (2013) Observed climate variability and change in Urmia Lake Basin, Iran. Theor Appl Climatol 111:285–296. doi:10.1007/s00704-012-0651-9

DOE (2010) Iran's Second National Communication to the UNFCCC. National Climate Change Office, Department of Environment, Tehran

Döll P, Müller Schmied H, Schuh C, Portmann FT, Eicker A (2014) Global-scale assessment of groundwater depletion and related groundwater abstractions: combining hydrological modeling with information from well observations and GRACE satellites. Water Resour Res. doi:10.1002/2014WR015595

Eimanifar A, Mohebbi F (2007) Urmia Lake (northwest Iran): a brief review. Saline Syst 3:1–8

Elledge J, Madani K (2012) The evolution of the upper St. Johns river restoration project. Proceedings of the Tenth International Conference on Hydroscience and Engineering (ICHE), Orlando, Florida

Esmaeili A, Moore F, Keshavarzi B (2014) Nitrate contamination in irrigation groundwater, Isfahan. Iran Environ Earth Sci:1–12. doi:10.1007/s12665-014-3159-z

Ettehad E (2010) Hydropolitics in Hirmand/Helmand international river basin: application of integrated water resources management. Master's thesis, Department of Urban and Rural Development, Faculty of Natural Resources and Agricultural Sciences, Swedish University of Agricultural Sciences, Uppsala, Sweden

Evans J (2009) 21st century climate change in the Middle East. Clim Chang 92:417–432

Faramarzi M, Abbaspour KC, Schulin R, Yang H (2009) Modelling blue and green water resources availability in Iran. Hydrol Process 23:486–501. doi:10.1002/hyp.7160

Farhadinejad T, Khakzad A, Jafari M, Shoaee Z, Khosrotehrani K, Nobari R, Shahrokhi V (2014) The study of environmental effects of chemical fertilizers and domestic sewage on water quality of Taft region, Central Iran. Arab J Geosci 7:221–229. doi:10.1007/s12517-012-0717-0

Fathian F, Morid S, Kahya E (2014) Identification of trends in hydrological and climatic variables in Urmia Lake basin, Iran. Theor Appl Climatol:1–22 doi:10.1007/s00704-014-1120-4

Fattahi S, Alipourfard S, Habibi H (2013) Analysis of determinants of mineral water consumption: the case of Tehran. Rev Contem Bus Res 2:41–55

Finkl CW (1995) Water resource management in the Florida Everglades: are 'lessons from experience' a prognosis for conservation in the future? J Soil Water Conserv 50:592–600

Fisher B (1928) Irrigation systems of Persia. Geogr Rev 18:302–306

Fitt RL (1953) Irrigation development in central Persia. J R Cent Asian Soc 40:124–133. doi:10.1080/03068375308731471

Foltz R (2002) Iran's water crisis: cultural, political, and ethical dimensions. J Agric Environ Ethics 15:357–380. doi:10.1023/A:1021268621490

Forootan E et al (2014) Separation of large scale water storage patterns over Iran using GRACE, altimetry and hydrological data. Remote Sens Environ 140:580–595. doi:10.1016/j.rse.2013.09.025

Garousi V, Najafi A, Samadi A, Rasouli K, Khanaliloo B (2013) Environmental crisis in Lake Urmia, Iran: a systematic review of causes, negative consequences and possible solutions. Paper presented at the Proceedings of the 6th International Perspective on Water Resources & the Environment (IPWE) Izmir, Turkey

Gerivani H, Lashkaripour GR, Ghafoori M (2011) The source of dust storm in Iran: a case study based on geological information and rainfall data Carpathian. J Earth Environ Sci 6:297–308

Ghazali S (2012) Relationship between level of water in Parishan Lake and surrounded wells with respect to excessive groundwater extraction. J Agric Econ Res 4:121–135

Gleeson T, Wada Y, Bierkens MFP, van Beek LPH (2012) Water balance of global aquifers revealed by groundwater footprint Nature 488:197–200

Gohari A, Eslamian S, Abedi-Koupaei J, Massah Bavani A, Wang D, Madani K (2013a) Climate change impacts on crop production in Iran's Zayandeh-Rud River Basin. Sci Total Environ 442:405–419. doi:10.1016/j.scitotenv.2012.10.029

Gohari A, Eslamian S, Mirchi A, Abedi-Koupaei J, Massah Bavani A, Madani K (2013b) Water transfer as a solution to water shortage: a fix that can backfire. J Hydrol 491:23–39. doi:10.1016/j.jhydrol.2013.03.021

Gohari A, Madani K, Mirchi A, Bavani AM (2014) System-Dynamics approach to evaluate climate change adaptation strategies for Iran's Zayandeh-Rud Water System. In: Proceedings of the World Environmental and Water Resources Congress 2014, 1598–1607. ASCE, Portland. doi:10.1061/9780784413548.158

Gohari A, Bozorgi A, Madani K, Elledge J, Berndtsson R (In Press) Adaptation of surface water supply to climate change in Central Iran. J Water Clim Chang. doi:10.2166/wcc.2013.189

Golian S, Mazdiyasni O, AghaKouchak A (2014) Trends in meteorological and agricultural droughts in Iran. Theor Appl Climatol:1–10 doi:10.1007/s00704-014-1139-6

Gosnell H, Kelly EC (2010) Peace on the river? Social-ecological restoration and large dam removal in the Klamath basin, USA. Water Altern 3:361–383

Graf WL (2013) Water resources science, policy, and politics for the Florida everglades. Ann Assoc Am Geogr 103:353–362

Hamilton JB, Curtis GL, Snedaker SM, White DK (2005) Distribution of anadromous fishes in the upper Klamath River watershed prior to hydropower dams—a synthesis of the historical evidence. Fisheries 30:10–20

Hardin G (1968) The tragedy of the commons. Science 162:1243–1248

Harnish RA, Sharma R, McMichael GA, Langshaw RB, Pearsons TN, Hilborn R (2014) Effect of hydroelectric dam operations on the freshwater productivity of a Columbia River fall Chinook salmon population Canadian. J Fish Aquat Sci 71:602–615

Hassanzadeh E, Zarghami M, Hassanzadeh Y (2012) Determining the main factors in declining the Urmia Lake level by using system dynamics modeling. Water Resour Manag 26:129–145

Hjorth P, Madani K (2013) Systems analysis to promote frames and mental models for sustainable water management. Proceedings of the 3rd World Sustainability Forum, November 2013, Sciforum Electronic Conference Series 3, f003. doi:10.3390/wsf3-f003

Hjorth P, Madani K (2014) Sustainability monitoring and assessment: new challenges require new thinking. J Water Resour Plan Manag 140:133–135. doi:10.1061/(ASCE)WR.1943-5452.0000411

Hojjati MH, Boustani F (2010) An assessment of groundwater crisis in Iran, case study: Fars province World Academy of Science. Eng Technol 4:427–431

Hollinshead SP, Lund JR (2006) Optimization of environmental water purchases with uncertainty. Water Resour Res 42, W08403. doi:10.1029/2005WR004228

Imandel K, Farshad AA, Mir-abdollah L (2000) Increasing trend of nitrate contamination of Tehran southwest groundwater aquifer of Iran Iranian. J Public Health 29:43–54

Izady A, Davary K, Alizadeh A, Ghahraman B, Sadeghi M, Moghaddamnia A (2012) Application of "panel-data" modeling to predict groundwater levels in the Neishaboor Plain, Iran. Hydrogeol J 20:435–447. doi:10.1007/s10040-011-0814-2

Jahani HR, Reyhani M (2007) Role of groundwater in Tehran water crisis mitigation. Proceedings of the International Workshop on Groundwater for Emergency Situations (GWES), Tehran, October 29–31

Jahed Khaniki GR, Zarei A, Kamkar A, Fazlzadehdavil M, Ghaderpouri M, Zarei A (2010) Bacteriological evaluation of bottled water from domestic brands in Tehran markets, Iran. World Appl Sci J 8(3):274–278

Jalali M (2005) Nitrates leaching from agricultural land in Hamadan, western Iran. Agric Ecosyst Environ 110:210–218. doi:10.1016/j.agee.2005.04.011

Jamali S, Abrishamchi A, Marino MA, Abbasnia A (2012) Climate change impact assessment on hydrology of Karkheh Basin, Iran. Proc ICE-Water Manag 166:93–104

Jamali S, Abrishamchi A, Madani K (2013) Climate change and hydropower planning in the Middle East: implications for Iran's Karkheh hydropower systems. J Energy Eng 139:153–160. doi:10.1061/(ASCE)EY.1943-7897.0000115

Janparvar M, Nairizi S (2007) Role of groundwater in Tehran water crisis mitigation. Paper presented at the Proceedings of the International Workshop on Groundwater for Emergency Situations (GWES), Tehran, October 29–31

Joekar-Niasar V, Ataie-Ashtiani B (2009) Assessment of nitrate contamination in unsaturated zone of urban areas: the case study of Tehran, Iran. Environ Geol 57:1785–1798. doi:10.1007/s00254-008-1464-0

Jomehpour M (2009) Qanat irrigation systems as important and ingenious agricultural heritage: case study of the qanats of Kashan, Iran. Int J Environ Stud 66:297–315. doi:10.1080/00207230902752629

Joodaki G, Wahr J, Swenson S (2014) Estimating the human contribution to groundwater depletion in the Middle East, from GRACE data, land surface models, and well observations. Water Resour Res 50:2679–2692

Kaffashi S, Shamsudin M, Radam A, Rahim K, Yacob M, Muda A, Yazid M (2011) Economic valuation of Shadegan International Wetland, Iran: notes for conservation. Reg Environ Chang 11:925–934. doi:10.1007/s10113-011-0225-x

Karbalaee F (2010) Water crisis in Iran. Paper presented at the Proceedings of the International Conference on Chemistry and Chemical Engineering (ICCCE) 1–3 Aug. 2010

Kareiva P, Marvier M, McClure M (2000) Recovery and management options for spring/summer chinook salmon in the Columbia River Basin. Science 290:977–979

Karimi H, Keshavarz T, Mohammadi Z, Raeisi E (2007) Potential leakage at the Khersan 3 Dam Site, Iran: a hydrogeological approach. Bull Eng Geol Environ 66:269–278

Katouzian MA (1978) Oil versus agriculture a case of dual resource depletion in Iran. J Peasant Stud 5:347–369. doi:10.1080/03066157808438052

Kerachian R, Karamouz M (2006) Optimal reservoir operation considering the water quality issues: a stochastic conflict resolution approach. Water Resour Res 42(12), W12401. doi:10.1029/2005WR004575

Keshavarz M, Karami E, Vanclay F (2013) The social experience of drought in rural Iran. Land Use Policy 30:120–129. doi:10.1016/j.landusepol.2012.03.003

Khatami S (2013) Nonlinear Chaotic and Trend Analyses of Water Level at Urmia Lake, Iran. M.Sc. Thesis report: TVVR 13/5012, ISSN: 1101–9824, Lund University, Lund, Sweden

Khatami S, Berndtsson R (2013) Urmia Lake watershed restoration in Iran: short- and long-term perspectives. Proceedings of the 6th International Perspective on Water Resources & the Environment (IPWE), January 2013, Izmir, Turkey

Lambton AKS (1938) The regulation of the waters of the Zāyande Rūd. Bulletin of the School of Oriental Studies, University of London. 9(3): 663–673

Latif M, Mousavi S, Afyuni M, Velayati S (2005) Investigation of nitrate pollution and sources in groundwater in Mashhad Plain. J Agric Sci Nat Resour 12:21–32

Lugeri N, Genovese E, Lavalle C, De Roo A (2006) Flood risk in Europe: analysis of exposure in 13 Countries vol EUR22525 EN. Institute for Environment and Sustainability (IES), Land Management and Natural Hazard Unit, Ispra (VA), Italy

Lugeri N, Kundzewicz Z, Genovese E, Hochrainer S, Radziejewski M (2010) River flood risk and adaptation in Europe—assessment of the present status. Mitig Adapt Strateg Glob Change 15:621–639

Lund J, Hanak E, Fleenor W, Bennett W, Howitt R, Mount J, Moyle P (2010) Comparing futures for the Sacramento-San Joaquin delta. University of California Press, Berkeley

Madani K (2003) Water resources management; a solution to present crisis in Iran. Proceedings of the 10th Iranian Civil Engineering Conference, Amir Kabir University of Technology (Tehran Polytechnic University), Tehran, Iran

Madani K (2007) A system dynamics approach to integrated watershed management. Hydrol Sci Technol 23:147–158

Madani K (2008) Reasons behind Failure of Qanats in the 20th Century. Paper presented at the World Environmental and Water Resources Congress 2008, Honolulu, Hawaii, ASCE, doi:10.1061/40976(316)77

Madani K (2010a) Game theory and water resources. J Hydrol 381:225–238. doi:10.1016/j.jhydrol.2009.11.045

Madani K (2010b) Towards sustainable watershed management: using system dynamics for integrated water resources planning. VDM Verlag Dr. Müller, Saarbrücken

Madani K (2014) Iran's water crisis: is there any hope? Presentation at the Iran's Natural Heritage: A Catalyst Symposium to Spark Measurable Change, Royal Geographical Society, London, UK, January 18, 2014, Available at: https://www.youtube.com/watch?v=PIY3JErgEqY

Madani Larijani K (2005a) Iran's water crisis: inducers, challenges and counter-measures. Proceedings of the ERSA 45th Congress of the European Regional Science Association, Vrije University, Amsterdam, The Netherlands, August 2005

Madani Larijani K (2005b) Watershed management and sustainability—A system dynamics approach (Case study: Zayandeh-Rud River Basin, Iran). Master's thesis, Department of Water Resources Engineering, Lund University, Lund, Sweden

Madani K, Dinar A (2012a) Cooperative institutions for sustainable common pool resource management: application to groundwater. Water Resour Res 48(9), W09553. doi:10.1029/2011WR010849

Madani K, Dinar A (2012b) Non-cooperative institutions for sustainable common pool resource management: application to groundwater. Ecol Econ 74:34–45. doi:10.1016/j.ecolecon.2011.12.006

Madani K, Dinar A (2013) Exogenous regulatory institutions for sustainable common pool resource management: application to groundwater. Water Resour Econ 2–3:57–76. doi:10.1016/j.wre.2013.08.001

Madani K, Hipel K (2011) Non-cooperative stability definitions for strategic analysis of generic water resources conflicts. Water Resour Manag 25:1949–1977. doi:10.1007/s11269-011-9783-4

Madani K, Lund JR (2011) A Monte-Carlo game theoretic approach for multi-criteria decision making under uncertainty. Adv Water Resour 34:607–616. doi:10.1016/j.advwatres.2011.02.009

Madani K, Lund J (2012) California's Sacramento–San Joaquin delta conflict: from cooperation to chicken. J Water Resour Plan Manag 138:90–99

Madani K, Mariño M (2009) System dynamics analysis for managing Iran's Zayandeh-Rud River Basin. Water Resour Manag 23:2163–2187. doi:10.1007/s11269-008-9376-z

Madani K, Zarezadeh M (2014) The significance of game structure evolution for deriving game-theoretic policy insights. Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics (SMC), San Diego, CA, USA, IEEE

Madani K, Rowan D, Lund J (2007) The next step in Central Valley flood management: connecting costs and benefits. Proceedings of the UCOWR Conference, 2007. Paper 17, http://opensiuc.lib.siu.edu/ucowrconfs_2007/17/

Madani K, Rouhani OM, Mirchi A, Gholizadeh S (2014a) A negotiation support system for resolving an international trans-boundary natural resource conflict. Environ Model Softw 51:240–249. doi:10.1016/j.envsoft.2013.09.029

Madani K, Sheikhmohammady M, Mokhtari S, Moradi M, Xanthopoulos P (2014b) Social planner's solution for the Caspian Sea conflict group. Decis Negot 23:579–596. doi:10.1007/s10726-013-9345-7

Manouchehri GR, Mahmoodian SA (2002) Environmental impacts of dams constructed in Iran. Int J Water Resour Dev 18:179–182. doi:10.1080/07900620220121738

Mianabadi H, Sheikhmohammady M, Mostert E, Van de Giesen N (2014) Application of the ordered weighted averaging (OWA) method to the Caspian Sea conflict. Stoch Env Res Risk A 28:1359–1372. doi:10.1007/s00477-014-0861-z

Mirchi A, Watkins D (2013) A systems approach to holistic total maximum daily load policy: case of Lake Allegan, Michigan. J Water ResourPlan Manag 139:544–553. doi:10.1061/(ASCE)WR.1943-5452.0000292

Mirchi A, Watkins DW Jr, Huckins CJ, Madani K, Hjorth P (2014) Water resources management in a homogenizing world: Averting the growth and underinvestement trajectory. Water Resour res. doi:10.1002/2013WR015128

Mirchi A, Watkins Jr D, Madani K (2010) Modeling for watershed planning, management, and decision making. Chapter 6 In: Vaughn JC (ed) Watersheds: management, restoration and environmental impact, pp 221–244, Nova Science Publishers, Hauppauge, NY, USA

Mirchi A, Madani K, Watkins D Jr, Ahmad S (2012) Synthesis of system dynamics tools for holistic conceptualization of water resources problems. Water Resour Manag 26:2421–2442. doi:10.1007/s11269-012-0024-2

Moazedi A, Taravat M, Jahromi HN, Madani K, Rashedi A, Rahimian S (2011) Energy-water meter: a novel solution for groundwater monitoring and management. Proceedings of the World Environmental and Water Resources Congress 2011, pp. 962–969, Palm Springs, California, ASCE, doi: 10.1061/41173(414)99

Mohammadi Z, Raeisi E, Bakalowicz M (2007) Method of leakage study at the karst dam site. A case study: Khersan 3 Dam, Iran. Environ Geol 52:1053–1065. doi:10.1007/s00254-006-0545-1

Mohebbi F, Ahmadi R, Azari AM, Esmaili L, Asadpour Y (2011) On the red coloration of Urmia Lake (Northwest Iran). Int J Aquat Sci 2:88–92

Moradi R, Koocheki A, Nassiri Mahallati M, Mansoori H (2013) Adaptation strategies for maize cultivation under climate change in Iran: irrigation and planting date management. Mitig Adapt Strateg Glob Chang 18:265–284. doi:10.1007/s11027-012-9410-6

Morid S, Smakhtin V, Moghaddasi M (2006) Comparison of seven meteorological indices for drought monitoring in Iran. Int J Climatol 26:971–985. doi:10.1002/joc.1264

Motagh M, Djamour Y, Walter TR, Wetzel H-U, Zschau J, Arabi S (2007) Land subsidence in Mashhad Valley, northeast Iran: results from InSAR, levelling and GPS. Geophys J Int 168:518–526

Motiee H, Monouchehri G, Tabatabai M (2001) Water crisis in Iran, codification and strategies in urban water. Paper presented at the Proceedings of the Workshops held at the UNESCO Symposium, Technical documents in Hydrology No. 45, Marseille, France

Mousavi SF (2005) Agricultural drought management in Iran. Water conservation, reuse, and recycling. In: Proceedings of an Iranian-American workshop. The National Academies Press, Washington, DC, pp 106–113

Mousavi SM, Shamsai A, Naggar MHE, Khamehchian M (2001) A GPS-based monitoring program of land subsidence due to groundwater withdrawal in Iran. Can J Civ Eng 28:452–464. doi:10.1139/l01-013

Najafi A, Vatanfada J (2011) Environmental challenges in trans-boundary waters, case study: Hamoon Hirmand Wetland (Iran and Afghanistan). Int J Water Resour Arid Environ 1:16–24

Najafi H, Bagheri A, Madani K (2013) The topology of generic shared water resources games: insights for the Lake Urmia Disaster. 6th International Conference on Water Resources and Environment Research, Koblenz, Germany

Nattagh N (1986) Agriculture and regional development in Iran. Middle East and North African Studies Press, Outwell

Nikbakht J, Tabari H, Talaee PH (2013) Streamflow drought severity analysis by percent of normal index (PNI) in northwest Iran. Theor Appl Climatol 112:565–573. doi:10.1007/s00704-012-0750-7

Norouzi H, AghaKouchak A, Madani K, Mirchi A, Farahmand A, Conway C (2013) Monitoring changes in water resources systems using high resolution satellite observations: Application to Lake Urmia. American Geophysical Union Fall Meeting 2013, AGU Fall Meeting, San Francisco, California, Abstract # H43O-04

Oloumi Zad S, Ravesteijn W, Hermans L, van Beek E (2013) Managing conflicts in water resources allocation: the case of Urumia Lake Basin, Iran. In: Brebbia CA (ed) River basin management VII. WIT Press, Southampton, pp 153–165

Plum N, Schulte-Wülwer-Leidig A (2014) From a sewer into a living river: the Rhine between Sandoz and Salmon. Hydrobiologia 729:95–106. doi:10.1007/s10750-012-1433-1

Powers K, Baldwin P, Buck EH, Cody BA (2005) Klamath River basin issues and activities: an overview. Congressional Research Service (CRS) Report for Congress, No. RL33098, Washington, DC

Raymond HL (1988) Effects of hydroelectric development and fisheries enhancement on spring and summer chinook salmon and steelhead in the Columbia River Basin. N Am J Fish Manag 8:1–24. doi:10.1577/1548-8675(1988)008<0001:EOHDAF>2.3.CO;2

Raziei T, Saghafian B, Paulo A, Pereira L, Bordi I (2009) Spatial patterns and temporal variability of drought in Western Iran. Water Resour Manag 23:439–455. doi:10.1007/s11269-008-9282-4

Razmkhah H, Abrishamchi A, Torkian A (2010) Evaluation of spatial and temporal variation in water quality by pattern recognition techniques: a case study on Jajrood River (Tehran, Iran). J Environ Manag 91:852–860. doi:10.1016/j.jenvman.2009.11.001

Read L, Madani K, Inanloo B (2014) Optimality versus stability in water resource allocation. J Environ Manag 133:343–354. doi:10.1016/j.jenvman.2013.11.045

Roozbahani R, Torabi Palatkaleh S, Karimi A (2011) Water deficit sharing: A new approach to conflict resolution among stakeholders in the watershed. Proceedings of the 19th International Congress on Modelling and Simulation, Perth, WA, Australia, December 12–16

Salami H, Shahnooshi N, Thomson KJ (2009) The economic impacts of drought on the economy of Iran: an integration of linear programming and macroeconometric modelling approaches. Ecol Econ 68:1032–1039. doi:10.1016/j.ecolecon.2008.12.003

Samadi M, Rahmani A, Sedehi M, Sonboli N (2009) Evaluation of chemical quality in 17 brands of Iranian bottled drinking waters. J Res Health Sci 9:25–31

Seyf A (2006) On the importance of irrigation in Iranian agriculture. Middle East Stud 42:659–673. doi:10.1080/00263200600642399

Seyf A (2009) Population and agricultural development in Iran, 1800–1906. Middle East Stud 45:447–460. doi:10.1080/00263200902853439

Sharifikia M (2013) Environmental challenges and drought hazard assessment of Hamoun Desert Lake in Sistan region, Iran, based on the time series of satellite imagery. Nat Hazards 65:201–217. doi:10.1007/s11069-012-0353-8

Sheikhmohammady M, Madani K (2008a) Bargaining over the Caspian Sea — The largest lake on the earth. Proceedings of the World Environmental and Water Resources Congress 2008, Honolulu, Hawaii, May 2008, ASCE, doi:10.1061/40976(316)262

Sheikhmohammady M, Madani K (2008) A descriptive model to analyze asymmetric multilateral negotiations, Proceedings of the UCOWR Conference, Paper 6, 2008, http://opensiuc.lib.siu.edu/ucowrconfs_2008/6

Sima S, Tajrishy M (2006) Water allocation for wetland environmental water requirements: the case of Shadegan Wetland, Jarrahi Catchment, Iran. Proceedings of the World Environmental and Water Resource Congress 2006, Omaha, Nebraska, ASCE

Sima S, Tajrishy M (2013) Using satellite data to extract volume–area–elevation relationships for Urmia Lake, Iran. J Great Lakes Res 39: 90–99. doi:10.1016/j.jglr.2012.12.013

Soltani G, Saboohi M (2009) Economic and social impacts of groundwater overdraft: The case of Iran. Paper presented at the Proceedings of the 15th Economic Research Forum (ERF) annual conference

Sophocleous M (2010) Review: groundwater management practices, challenges, and innovations in the High Plains aquifer, USA—lessons and recommended actions. Hydrogeol J 18:559–575. doi:10.1007/s10040-009-0540-1

Tajziehchi S, Monavari S, Karbassi A, Shariat S, Khorasani N (2013) Quantification of social impacts of large hydropower dams—a case study of Alborz Dam in Mazandaran Province, Northern Iran. Int J Environ Res 7:377–382

Tanaka SK, Connell-Buck CR, Madani K, Medellin-Azuara J, Lund JR, Hanak E (2011) Economic costs and adaptations for alternative regulations of California's Sacramento-San Joaquin Delta San Francisco. Estuary Watershed Sci 9:1–28

van Dijk GM, Marteijn ECL, Schulte-Wülwer-Leidig A (1995) Ecological rehabilitation of the River Rhine: plans, progress and perspectives Regulated Rivers. Res Manag 11:377–388. doi:10.1002/rrr.3450110311

Verchick RR (1999) Dust bowl blues: saving and sharing the Ogallala Aquifer. J Environ Law Litig 14:13–23

Vojdani F (2004) Efficiency in water planning and management (an implementation experience). Water Supply 4:67–80

Wieriks K, Schulte-Wülwer-Leidig A (1997) Integrated water management for the Rhine river basin, from pollution prevention to ecosystem improvement. Nat Res Forum 21:147–156

Wohlers T, Mason A, Wood J, Schmaltz E (2014) Tragedy of the commons meets the anti-commons: water management and conflict on the southern plains of the United States. JEnviron Assess Pol Manag 16:1450005. doi:10.1142/S1464333214500057

Wulff HE (1968) The qanats of Iran. Sci Am 218:94–105

Yazdanpanah M, Hayati D, Zamani G, Karbalaee F, Hochrainer-Stigler S (2013a) Water management from tradition to second modernity: an analysis of the water crisis in Iran. Environ Dev Sustain 15:1605–1621. doi:10.1007/s10668-013-9452-2

Yazdanpanah M, Thompson M, Hayati D, Zamani GH (2013b) A new enemy at the gate: tackling Iran's water super-crisis by way of a transition from government to governance. Prog Dev Stud 13:177–194. doi:10.1177/1464993413486544

Zamani-Ahmadmahmoodi R, Esmaili-Sari A, Savabieasfahani M, Ghasempouri S, Bahramifar N (2010) Mercury pollution in three species of waders from Shadegan Wetlands at the head of the Persian Gulf. Bull Environ Contam Toxicol 84:326–330. doi:10.1007/s00128-010-9933-z

Zarezadeh M, Madani K, Morid S (2013) Resolving conflicts over transboundary rivers using bankruptcy methods. Hydrol Earth Syst Sci Discuss 10:13855–13887. doi:10.5194/hessd-10-13855-2013

Zarghami M, Abdi A, Babaeian I, Hassanzadeh Y, Kanani R (2011) Impacts of climate change on runoffs in East Azerbaijan, Iran. Glob Planet Chang 78:137–146. doi:10.1016/j.gloplacha.2011.06.003

Zeinoddini M, Tofighi MA, Vafaee F (2009) Evaluation of dike-type causeway impacts on the flow and salinity regimes in Urmia Lake, Iran. J Great Lakes Res 35:13–22

Zeinoddini M, Bakhtiari A, Ehteshami M (2014) Long-term impacts from damming and water level manipulation on flow and salinity regimes in Lake Urmia, Iran. Water Environ J. doi:10.1111/wej.12087

Zekri S (2009) Controlling groundwater pumping online. J Environ Manag 90:3581–3588. doi:10.1016/j.jenvman.2009.06.019