Journal of Hydrology 491 (2013) 23–39

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Water transfer as a solution to water shortage: A fix that can Backfire

Alireza Gohari [a,d,*], Saeid Eslamian [a], Ali Mirchi [b], Jahangir Abedi-Koupaei [a], Alireza Massah Bavani [c], Kaveh Madani [d]

[a] Department of Water Engineering, College of Agriculture, Isfahan University of Technology, Isfahan, Iran
[b] Department of Civil and Environmental Engineering, Michigan Technological University, Houghton, MI 49931, USA
[c] Department of Irrigation and Drainage Engineering, College of Abureyhan, University of Tehran, Iran
[d] Department of Civil, Environmental and Construction Engineering, University of Central Florida, Orlando, FL 32816, USA

ARTICLE INFO

Article history:
Received 19 October 2012
Received in revised form 13 March 2013
Accepted 16 March 2013
Available online 27 March 2013
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
System dynamics
Water resources management
Water transfer
Zayandeh-Rud
Gav-Khouni
Iran

SUMMARY

Zayandeh-Rud River Basin is one of the most important basins in central Iran, which has been continually challenged by water stress during the past 60 years. Traditionally, a supply-oriented management scheme has been prescribed as a reliable solution to water shortage problems in the basin, resulting in a number of water transfer projects that have more than doubled the natural flow of the river. The main objective of this study is to evaluate the reliability of inter-basin water transfer to meet the growing water demand in Zayandeh-Rud River Basin. A system dynamics model is developed to capture the interrelationships between different sub-systems of the river basin, namely the hydrologic, socioeconomic, and agricultural sub-systems. Results from simulating a range of possible policy options for resolving water shortage problems indicate that water is essentially the development engine of the system. Therefore, supplying more water to the basin without considering the dynamics of the interrelated problems will eventually lead to increased water demand. It is demonstrated that the Zayandeh-Rud River Basin management system has characteristics of the "Fixes that Backfire" system archetype, in which inter-basin water transfer is an inadequate water management policy, causing significant unintended side-effects. A comprehensive solution to the problem includes several policy options that simultaneously control the dynamics of the system, minimizing the risk of unintended consequences. In particular, policy makers should consider minimizing agricultural water demand through changing crop patterns as an effective policy solution for the basin's water problems.

1. Introduction

Water scarcity resulting from economic and population growth is considered as one of the most important threats for human societies and a constraint for sustainable development (UN-Water, 2008). Within the next decades, water may become the most strategic resource, especially in arid and semi-arid regions of the world (UN-Water, 2005). Historically, policy makers in these regions have tried to solve water scarcity problems through dam building, groundwater recharge, cloud seeding, desalination, wastewater reuse, and developing massive water transfer projects, among others (Hutchinson et al., 2010). However, there is a growing body of evidence that water scarcity can be created or intensified by unsustainable decisions to meet the increasing water demands (Gleick, 1998; Cai et al., 2003). In arid regions, supply-oriented water management schemes, although promising in the short-run, are typically associated with unintended secondary consequences in the long run (Madani and Mariño, 2009). In essence, the failure to develop sustainable water resources solutions at watershed scale is rooted in the lack of understanding about the interrelated dynamics of different sub-systems of complex watershed systems (Mirchi et al., 2010).

Zayandeh-Rud River Basin is one of the most strategic Iranian watersheds due to its significant agricultural, as well as industrial and environmental importance. In the past decades, growing population, driven by urbanization, industrial, and agricultural development, coupled with occurrence of severe droughts have significantly increased water stress in the basin. To address this problem, different conventional engineering solutions have been practiced since 1952, including a multi-purpose reservoir and three inter-basin water transfer projects. Given the inadequacy of these projects to solve the water shortage problems, three additional inter-basin water transfer projects are currently under

* Corresponding author. Present address: Hydro-Environmental and Energy Systems Analysis (HEESA) Research Group, Department of Civil, Environmental and Construction Engineering, University of Central Florida, Orlando, FL 32816, USA. Tel.: +98 311 391 3432, +1 407 823 2317; fax: +98 311 391 2254, +1 407 823 3315.
E-mail addresses: alireza.gohari@ucf.edu (A. Gohari), saeid@cc.iut.ac.ir (S. Eslamian), amirchi@mtu.edu (A. Mirchi), koupai@cc.iut.ac.ir (J. Abedi-Koupaei), armassah@ut.ac.ir (A. Massah Bavani), kaveh@ucf.edu (K. Madani).

0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.03.021

development to increase the water supply of the basin within the next decade.

Inter-basin water transfer from water-abundant regions (donors) to regions with water shortages (recipients) has been recognized as a solution to secure water supply for supporting development in recipient basins (Muller, 1999; Allan, 2003; Ballestero, 2004; Dyrnes and Vatn, 2005; Gupta and van der Zaag, 2008). Thus, numerous water transfer projects have been implemented around the world (e.g., Australia (Wright, 1999), China (Shao et al., 2003), Germany (Schumann, 1999), Iran (Abrishamchi and Tajirshy, 2005; Bagheri and Hjorth, 2007; Madani and Mariño, 2009), Mexico (Medellin-Azuara et al., 2011), and the United States (Israel and Lund, 1995; Varady, 1999; Lund et al. 2010; Medellin-Azuara et al., 2011; Madani and Lund, 2012)). Worldwide, approximately 14% of global water withdrawal is provided through inter-basin water transfer projects and this portion is expected rise to 25% by 2025 (ICID, 2005). Water transfer initiatives have relieved water stress by providing "sufficient" water for different users (Muller, 1999; Ballestero, 2004), enhancing socioeconomic development (Israel and Lund, 1995; Klaphake, 2005; Gupta and van der Zaag, 2008), and increasing freshwater availability for ecosystem augmentation in the recipient basins (Scheuerlein, 1999; Gichuki and McCornick, 2008). However, water transfer may entail negative long-term social, economic, and environmental impacts, raising concern as to its effectiveness as a panacea to water shortage (Matete and Hassan, 2006; Klein, 2007; Kittinger et al., 2009; Growns et al., 2009; Olden and Naiman, 2010; Yan et al., 2012). It has been argued that the need for additional water supply in water-deficient regions increases when water shortage is addressed through water transfers with no control on water demand (Gichuki and McCornick, 2008).

Investigating the reasons for success or failure of water transfer projects can provide valuable lessons to water resources planners and policy makers, who have historically based their decisions on a simple comparison of water balances in the recipient and donor basins (Andrade et al., 2011). Water transfer decisions should be based on a holistic view of the problem, which not only includes the hydrological aspects, but also the socioeconomic and environmental concerns. Developing integrated water resources management models can facilitate a holistic understanding of complex watershed systems, leading to sustainable water resources planning and management decisions (Madani, 2007; Mirchi et al., 2010). System dynamics models are tools that facilitate understanding of the interactions among diverse but interconnected sub-systems that drive the dynamic behavior of the system (Forrester, 1961, 1969; Meadows et al., 1972; Richmond, 1993; Ford, 1999; Sterman, 2000). These models can facilitate water resources planning and management by identifying problematic trends and their root drivers within an integrated framework (Mirchi et al., 2012), which is critical for sustainable management of water resources systems (Hjorth and Bagheri, 2006; Madani, 2010).

This study presents an integrated system dynamics model, the Zayandeh-Rud Watershed Management and Sustainability Model 2.0 (ZRW-MSM 2.0), to evaluate water resources sustainability in the Zayandeh-Rud River Basin. The model is an extension to the ZRW-MSM, developed by Madani and Mariño (2009). In addition to providing an improved database, ZRW-MSM 2.0 allows for simulation of the agricultural sub-system which was not included in the original version of the model. Given the importance of agriculture, as the main water consumer in the basin, this improvement is essential for comprehensive understanding of the Zayandeh-Rud River Basin's water stress problem. The specific objectives of this study include: (1) examining the adequacy of water transfer as a reliable long-term solution to water shortage in the Zayandeh-Rud River Basin; (2) evaluating the impacts of inter-basin water transfers on social, economic, environmental, and hydrological sub-systems of Zayandeh-Rud River Basin system; (3) understanding the effects of different water management strategies and policies on the system and its sub-systems; and (4) identifying sustainable solutions to water scarcity in the basin. A description of the study area and an overview of system dynamics and its application in water resources management are given in Sections 2 and 3. Sections 4 and 5 discuss the model development process and the results under different policy options for resolving water shortagein the basin. The policy implications of the study and conclusions are given in Sections 6 and 7.

2. Zayandeh-Rud River Basin

The Zayandeh-Rud River Basin (Fig. 1) covers an area of about 26,917 km^2 in central Iran. Table 1 summarizes some of the main characteristics of the basin. The population of the basin increased from 3.1 million in 1996 to 3.7 million in 2006. More job opportunities and a higher economic growth relative to the neighboring basins are the major reasons for immigration to the basin (Madani, 2005). The basin contains six irrigation networks, located mostly in the upper sub-basins that supply water for agriculture, which is the major water consumer. The main traditional staple crops of the basin are wheat, rice, barley, and corn, which are highly water consumptive. Irrigation is essential due to low precipitation coupled with asynchrony between rainy and growing seasons (Zayandab Consulting Engineering Co., 2008). Like in other parts of Iran, low irrigation efficiency of 34–42% is considered as one of the main reasons for high agricultural water demands.

The basin has a number of surface and groundwater resources. Zayandeh-Rud River with an average flow of 1400 million cubic meters (MCM), including 650 MCM of natural flow and 750 MCM of transferred flow, is the main surface water resource of the basin. The river eventually flows into the Gav-Khouni Marsh in the east of the basin. Gav-Khouni is an internationally recognized marsh under the Ramsar Convention on Wetlands (1971) and the basin's main ecological resource (Mansoori, 1997; Madani and Mariño, 2009). Nevertheless, due to aggressive upstream water uses, Gav-Khouni does not receive its minimum water share from the Zayandeh-Rud River, triggering severe ecosystem degradation in the system, which has caused the marsh to be considered an already dead wetland by many environmental activists (Evans, 1994; Vakili, 2006; Nikouei et al., 2012). Groundwater is the other major water resource of the basin. Over 22 confined and unconfined aquifers provide 369,000 MCM of hydrostatic groundwater storage for the basin (Zayandab Consulting Engineering Co., 2008).

Gav-Khouni Marsh has received large inflows only for a short period of time after implementation of each water transfer project, causing ecological water shortage in the basin. Fig. 2 shows the historical trend of water use and associated impacts on inflow to Gav-Khouni Marsh. The figure illustrates the basin's water resources expansion over time, as well as episodes of water shortage due to anthropocentric or natural scarcity. Before 1953 irrigation water was provided through springs and qanats (English, 1968; Wulff, 1968; Motiee et al., 2006; Madani, 2008), and early summer snowmelt. Water resources development was limited to traditional small diversion structures that provided water for small farm lands. In response to increasing water demand post World War II, the first water transfer infrastructure, Kuhrang Tunnel No. 1, was constructed and began operation in 1953. The basin's second water resources development project was the Chadegan (Zayandeh-Rud) Dam, with a capacity of 1500 MCM, which was built in 1971 for flood control and agricultural water supply. At that time agricultural water demand was growing with the construction of modern irrigation and drainage networks (Morid, 2003). By the early 1980s water demand had reached the limit of water supply

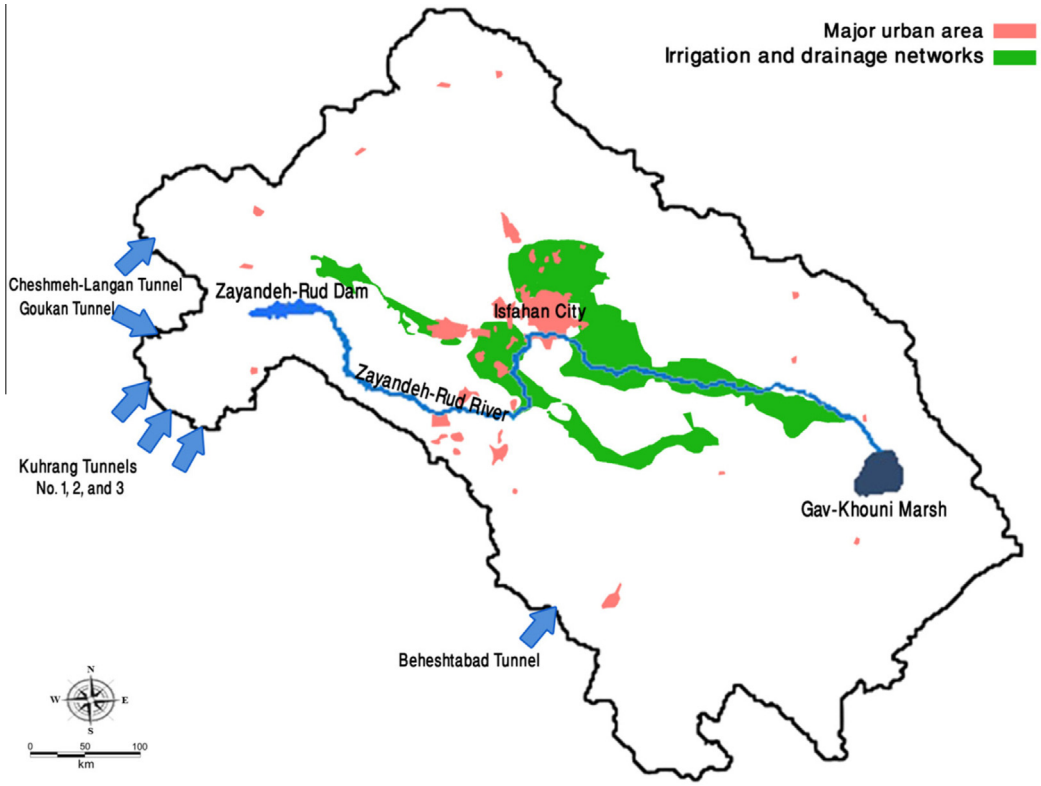

Fig. 1. The Zayandeh-Rud River Basin. Blok arrows illustrate inlets of inter-basin water transfer projects, and polygons show the geographical extent of major uses.

Table 1
General characteristics of the basin.

Attribute	Value
Physiographic and hydrologic	
Elevation range (m)	1470–3974
Annual average precipitation range (mm)	50–1500
Average temperature range (°C)	3–30
Annual potential evapotranspiration (mm)	1500
Average Humidity (%)	24–57
River length (km)	350
Average natural flow (MCM)	650
Average transferred flow (MCM)	750
Urban	
Population in 2006 (capita)	3,710,889
Population growth rate (%)	1.5
Domestic water use (%)	17
Industrial	
Industrial water use (%)	10
Agricultural	
Irrigation efficiency (%)	34–42
Agricultural water use (%)	73
Irrigated area (ha)	270,000
Rain fed area (ha)	30,000
Groundwater	
Water supply from groundwater resources (%)	72
Groundwater supply from wells (%)	83
Groundwater supply from qanats (%)	12
Groundwater supply from springs (%)	5
Demand	
Per capita urban water demand (Liter)	240
Per capita rural water demand (Liter)	150
Gav-Khuoni Marsh minimum required input flow (MCM)	140

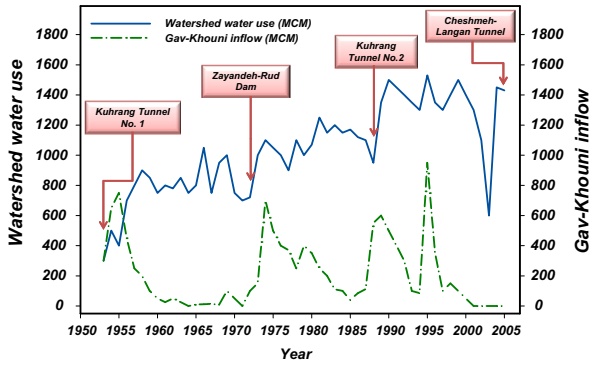

Fig. 2. The historical trend of water use and inflow to Gav-Khouni Marsh (Isfahan Regional Water Company, unpublished data).

and the basin was facing serious water shortages. The third water resources development project of the basin was Kuhrang Tunnel No. 2, which started to operate in 1985 to transfer water for agricultural development, as well as satisfying domestic and industrial water demands. During the last years of the 20th century droughts reduced the discharges of the two Kuhrang Tunnels. Consequently, water level in the Chadegan Reservoir dropped significantly and considerable groundwater overdraft occurred. As the demand continued to grow, Cheshmeh-Langan Tunnel was finalized in 2005 as the third water transfer infrastructure of the basin. The three water transfer tunnels have more than doubled the natural flow of Zayandeh-Rud River (Table 2).

Despite its recurring water deficit, since 2002 the Zayandeh-Rud River Basin has become a donor basin, providing 257 MCM of water to urban areas in the neighboring basins (Table 3). Given the ongoing water shortage problems and the inadequacy of the total available water to meet the needs of the basin, and to donate sufficient water to other basins, two other water transfer projects (Goukan Tunnel and Kuhrang Tunnel No. 2) are nearing completion

Table 2
Transfer projects importing water to Zayandeh-Rud River Basin.

Name of project	Year of completion	Annual capacity (MCM)[a]	Length (m)[b]	Donor basin
Kuhrang Tunnel No. 1	1954	330	2800	Karoun River Basin
Kuhrang Tunnel No. 2	1985	250	2827	Karoun River Basin
Cheshmeh-Langan Tunnel	2005	164	8130	Dez River Basin
Goukan Tunnel	2015 (expected)	150	20,000	Dez River Basin
Kuhrang Tunnel No. 3	2016 (expected)	280	49,230	Karoun River Basin
Beheshtabad Tunnel	Under study	1100	64,970	Karoun River Basin

[a] Zayandab Consulting Engineering Co. (2008).
[b] Source: Isfahan regional water company (http://www.esrw.ir).

Table 3
Transfer projects exporting water from Zayandeh-Rud River Basin.

Name of project	Annual capacity (MCM)[a]	Recipient city
Yazd water transfer	100	Yazd
Golab water transfer	35	Kashan
Ardestan city water transfer	15	Ardestan and Natanz
Shahrekord city water transfer	25	Shahrekord
Jarghouyeh city water transfer	45	Jarghouyeh
Naeen city water transfer	37	Naeen and Khour-o-Biabanak

[a] Zayandab Consulting Engineering Co. (2008).

to bring additional water to the basin. Furthermore, the feasibility of transferring an additional 1100 MCM of water to Zayadeh-Roud, Yazd, and Kerman through a new water transfer facility (Beheshtabad Tunnel) is currently being studied. Tables 2 and 3 present some basic characteristics of the incoming and outgoing water transfer projects of the basin.

As discussed by Madani and Mariño (2009) "the Zayandeh-Rud River Basin is an example of a complicated watershed system where the lack of complete knowledge about all the interacting sub-systems has led to failure of the policymakers in addressing the water shortage in the basin." High industrial and agricultural potentials are the main drivers of development in the basin, encouraging in-migration. Without consideration of the possible secondary effects, the supply-oriented water transfer has been the primary policy, matching water supply and demand in the basin. However, each water transfer has solved the water shortage problem only for a short period as water demand has increased in parallel with water supply—a trend that will likely continue and/or exacerbate with time. In recent years, the basin has witnessed an unprecedented pressure on water resources, especially in agricultural sectors. Gav-Khouni Marsh is drying and its ecosystem has been damaged. The winter census of Isfahan Environmental Organization shows that the number of migratory birds in this marsh has decreased by more than 90% during the last decade (Soltani, 2009). A holistic view of the different problem drivers and their interactions helps develop an effective solution for providing a sustainable water supply in the basin. Following Madani and Mariño (2009), system dynamics is used in this study to understand the main causes of the past failure, and suggest reliable policy solutions to the problem.

3. System dynamics

Systems thinking helps recognize water resources as a system that includes disparate but interacting parts, which functions as a unit that must be treated as a whole (Simonovic, 2009). System dynamics, which is based on dynamic and closed loop theories of systems thinking, is a method to capture the complex systems and monitor their dynamic behavior (Forrester, 1961; Sterman, 2000). Due to the complex nature of water resources management problems, they have been highly resistant to solutions developed based on linear thinking or an event-oriented view of problems (Hjorth and Bagheri, 2006; Simonovic, 2009; Mirchi et al., 2012). Therefore, a shift from looking at isolated problems and their causes to systematic thinking about water problems is essential for developing effective solutions. System dynamics provides a framework to see interrelationships and processes rather than individual components, and for capturing patterns of change rather than static snapshots of the problem (Simonovic and Fahmy, 1999). It can thus be a suitable approach to capture problematic trends of water resources and their root causes in an integrated framework. System dynamics models can reproduce the system's response to interventions over time, which facilitates addressing the existing problems at appropriate scale and scope (Winz et al., 2009; Mirchi et al., 2012). However, the ability of these models to provide insights into potential consequences of system perturbation are dependent on efficiently recognizing the main components and feedback loops between them (Madani and Mariño, 2009; Simonovic, 2009; Mirchi et al., 2012).

In the field of water resources, system dynamics has been used for water quality and environmental planning (Vezjak et al., 1998; Guo et al., 2001; Tangirala et al., 2003; Leal Neto et al., 2006; Venkatesan et al., 2011; Mirchi and Watkins, in press), flood management (Ahmad and Simonovic, 2000, 2004; Simonovic and Li, 2003), emergency planning and crisis management (Simonovic and Ahmad, 2005; Bagheri et al., 2010), reservoir operation (Ahmad and Parshar, 2010), drought impact assessment (Shahbazbegian and Bagheri, 2010); participatory water modeling (Ford, 1996; Stave, 2003; Tidwell et al., 2004; Langsdale et al., 2007, 2009), and water resources policy analysis, management, and decision-making (Simonovic and Fahmy, 1999; Xu et al., 2002; Simonovic and Rajasekaram, 2004; Stewart et al., 2004; Sehlke and Jacobson, 2005; Bagheri and Hjorth, 2007; Gastélum et al., 2009; Madani and Mariño, 2009; Ahmad and Parshar, 2010; Davies and Simonovic, 2011; Qaiser et al., 2011; Hassanzadeh et al., 2012). More extensive reviews of system dynamics applications in water resources can be found in Winz et al. (2009) and Mirchi et al. (2012).

Many water resources management models capture hydrological and related natural processes in water resources systems exclusively and assume socioeconomic aspects of these systems as exogenous drivers (Draper et al., 2003; Jenkins et al., 2004; Zhu et al., 2007; Medellin-Azuara et al., 2008; Maneta et al., 2009; Connell-Buck, 2011; Tanaka et al., 2011). In contrast, system dynamics models provide a holistic framework to focus on the interacting natural and socioeconomic processes in water systems as a whole. This ability of system dynamics is the main reason for its widespread application in water resources planning and management problems in the last century. Despite the growing applications of system dynamics in the water resources field, Mirchi et al. (2012) argue that "the field of water resources has not utilized the full capacity of system dynamics in the thinking phase of

integrated water resources studies", advocating that more emphasis should be put on the qualitative modeling phase of system dynamic analysis for better understanding of complex water resources systems. Following their cautionary suggestion, this study pays particular attention to the qualitative modeling stage of the problem to identify the main drivers of the undesired issues in the basin. Running a quantitative system dynamics model, which is based on a detailed qualitative causal model, facilitates understanding the complex causal relationships within the Zayandeh-Rud system. This approach helps simplify the extensive qualitative and quantitative models of the problem to a simple causal-descriptive model, which clearly reflects the archetypal behavior of the system, as discussed later in Section 6.

4. Model development

The first and foremost step in system dynamics modeling is to determine the system's structure, consisting of positive and negative casual relationships between components and feedback loops (Sterman, 2000). In a positive causal relationship, an increase/decrease in one variable causes an increase/decrease in the other variable. The opposite is true for a negative causal relation between two variables. Combinations of positive and negative casual relationships form feedback loops. Fundamentally, there are two types of feedback loops: reinforcing (positive) loop and balancing (negative) loop. Balancing feedback loops have a target-oriented behavior, i.e., if some changes drive the system to shift away from its goal, the balancing feedback loop tries to neutralize the effects of that shift, and return the system to its initial condition. This feedback loop is characterized by trends of growth-decline or decline-growth (oscillation around the equilibrium point). In contrast, reinforcing feedback loops are considered as driving factors of a system, whose archetypal behavior is characterized by continuous trends of growth or decline (Sterman, 2000; Simonovic, 2009; Mirchi et al., 2012). As reinforcing feedback loops rarely drive an isolated system, pure continuous growth or decline does not typically occur in nature. The effects of reinforcing loops will be eventually neutralized or reduced by balancing loop(s) in complex purely natural systems (Bender and Simonovic, 1996; Madani and Mariño, 2009).

Generally, the qualitative analysis phase of a system dynamics study involves two major steps: (1) developing a conceptual model or casual loop diagram (CLD) of the problem; and (2) developing the stock and flow diagram (SFD) of the problem based on its CLD. A CLD of the system, which is developed using an evolutionary approach, represents holistic understanding of the system structure, determining its boundaries, and identifying the key variables (Simonovic, 2009). In the next step, SFDs are developed to provide a clear picture of the stock and flow structure of the system (Madani and Mariño, 2009; Mirchi et al., 2012). In the system dynamics context, the main variables are either stocks, i.e., the state of the system, or they are flows, which reflect the rates by which the stock variables change (Simonovic, 2009). A classic example of a stock variable in the water resources context is water storage in a reservoir that changes by the inflows and outflows, as flow variables.

4.1. Casual loop diagram

The CLD of the supply-oriented water management problem in the Zayandeh-Rud River Basin is comprised of hydrologic, socioeconomic, and agricultural sub-systems. Each sub-system includes different drivers of the basin's water resources system development.

4.1.1. Hydrological sub-system

The CLD of the hydrological sub-system represents regional elements of the hydrologic cycle, water supply, and ecosystem (e.g., Gav-Khouni Marsh). The inter-basin water transfer projects, groundwater and surface water interaction, regional hydrology, and water supply are the main components of this sub-system (Fig. 3). As illustrated in Fig. 3, regional climatologic and hydrologic attributes such as temperature, precipitation, evapotranspiration, runoff, and natural flows, as well as groundwater recharge govern the basin's natural water balance. The CLD shows the dynamics among these components using polarized arrows denoting positive and/or negative causal relationships. Furthermore, the CLD shows the supply-oriented human interventions (e.g., inter-basin water transfer) that have increased water availability to satisfy growing demand. The ordinal priorities of water allocation in the basin are considered as domestic, industrial, agricultural, and finally, environmental. Surface water is the first choice to meet these demands while groundwater is used when the surface water supply is not available. The return flow from non-consumptive portion of the water use from various sectors is fed back to the system in the form of surface water and groundwater recharge. Gav-Khouni Marsh is considered as the downstream physical boundary of the system whose natural inflow has inevitably reduced due to persistence of severe water shortages and the existing priority order for meeting demands.

4.1.2. Socioeconomic sub-system

The CLD of the socioeconomic sub-system is shown in Fig. 4. Water demand in the basin is driven by the state of socioeconomic development, which in turn impacts the residents' utility, as well as drives in-migration from neighboring basins (Madani and Mariño, 2009). National economic growth rate is an exogenous economic factor that affects the overall attractiveness of living conditions nationwide, including the Zayandeh-Rud River Basin. It is assumed that a combination of per capita water use, added value from water use, national economic growth rate, and the watershed's GRP relative to neighboring regions, determines the residents' utility. The residents' utility is a proxy for the economic development in the basin and the residents' satisfaction from the available job opportunities, services, and goods, which triggers in-migration from neighboring basins (Madani and Mariño, 2009). Faster economic growth in the basin, as compared to neighboring basins, will lead to relatively more rapid development, which will increase job opportunities, encouraging in-migration, and raising water use by various use sectors. Thus, the residents' utility heightens the socioeconomic development, raising the per capita water use. The increase in per capita water use increases the growth rate of sectoral per capita water demand. Consequently, the basin's total water demand, determined as the summation of agricultural, industrial and domestic water demands, increases as well. Since economic productivity emanating from water use is different for industrial, domestic, and agricultural uses, the added value has been defined as the summation of economic productivity for different use sectors. When water supply is not a constraint, increasing water demand will lead to an increase in the sectoral water use. The basin's water use-related productivity will put this basin at an advantage in relation to neighboring basins, making it a more attractive place to reside in, which will ultimately increase water demand in what appears to be a reinforcing process.

4.1.3. Agricultural sub-system

More than 70% of the supplied water is allocated to the basin's agricultural sector (Gohari et al., 2013). A variety of irrigated crops are cultivated in the basin. The irrigation water demand for production of ten different crops and/or class of crops has been considered in this study, including wheat, barley, potato, rice, onion,

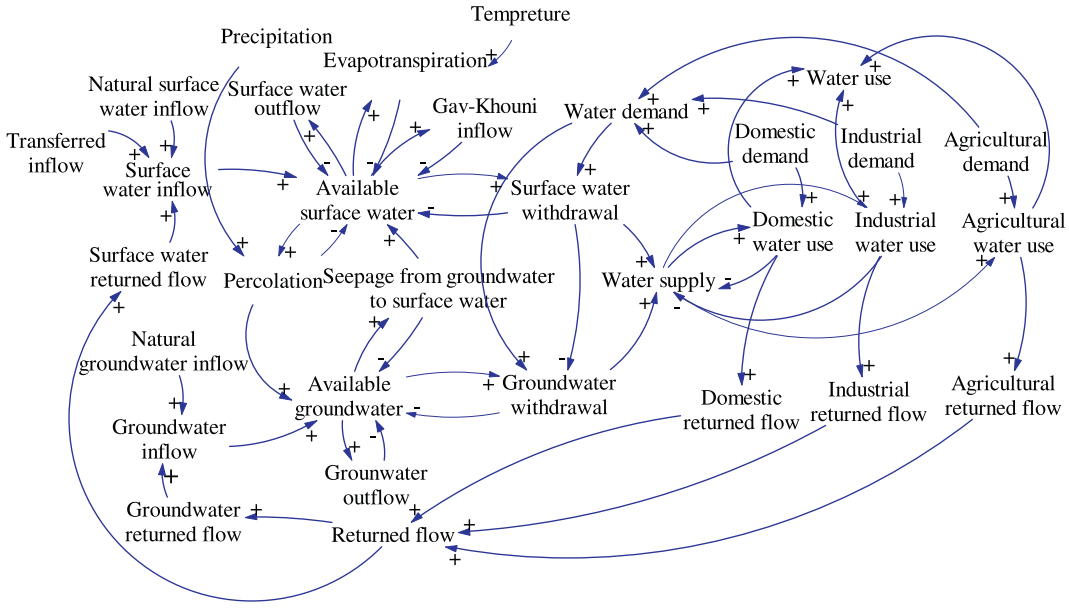

Fig. 3. CLD of the hydrological sub-system.

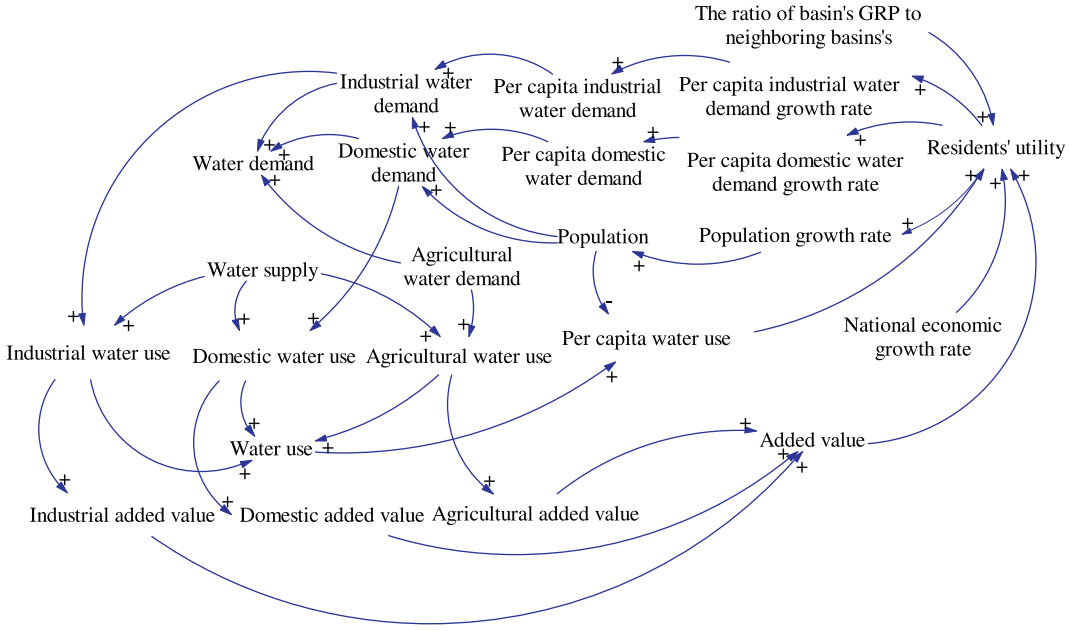

Fig. 4. CLD of socioeconomic sub-system.

alfalfa, corn, garden products, vegetables, and cereal and legume. The CLD of agricultural sub-system for two hypothetical crops is shown in Fig. 5. It is assumed that decisions pertaining to crop production levels and crop-based agricultural land use are based on income-maximizing behavior of the farmers. Therefore, the land area for each crop is assumed to be a function of its net economic benefit in the previous year. Both expected land area and irrigation water requirement for each crop have positive relationships with expected water requirement for the corresponding crop. The basin's expected agricultural water requirement, which is calculated as the sum of expected water requirement of all crops, determines the net agricultural water demand. Furthermore, agricultural water demand has a negative causal relationship with irrigation efficiency. It is noteworthy that the basin's agricultural water demand is only partially satisfied due to unavailability of sufficient irrigation water. Thus, "delivery rate" is defined as the proportion of agricultural water demand that can be satisfied using available irrigation water supply. Agricultural water demand and water supply have positive relations with agricultural water use. High agricultural water use when coupled with high irrigation efficiency will result in minimal loss of water, increasing the net agricultural water consumption. The actual land area for each crop is determined by modifying the expected land area for the corresponding crop based on the delivery rate, which is positively related with actual land area.

An agricultural market is simulated to calculate the net economic benefit from each crop. The production of each crop increases as a result of increase in actual land area that is allocated to that crop. The crop price is determined as a function of its production in the same year and is negatively related to the

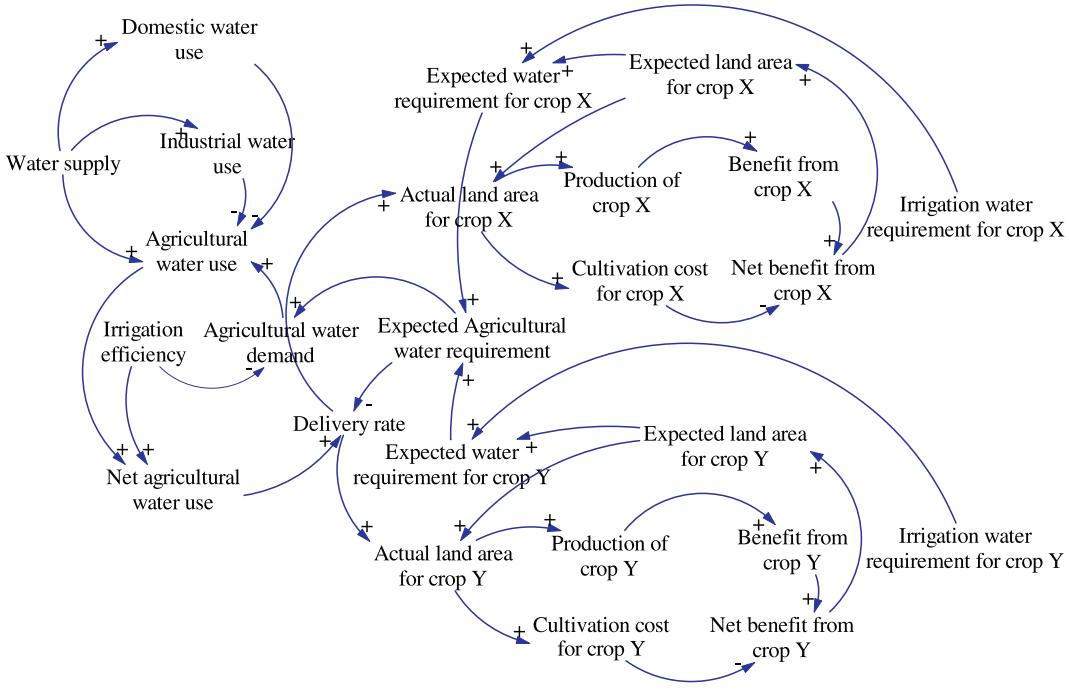

Fig. 5. CLD of agricultural sub-system.

production level. The benefit from each crop, which has a positive causal relationship with production, is considered to be the sum of benefits from the crop product, as well as benefits from the crop's by-products. The cultivation cost for each crop rises with the actual land area, and includes the cost of seeds, labor, fertilizer, and pesticide. In this study, the price of water is not considered as a significant component of the cultivation cost for irrigation water is highly subsidized in the basin, and there are many political obstacles against raising the price of agricultural water (Madani and Mariño, 2009). The dynamic market of each crop is assumed to be independent from the others whereas, in actuality, dependence may be observed in dynamic markets or cultivation of different crops.

4.2. Stock and flow diagram

The SFD of the hydrological and socioeconomic sub-systems are shown in Figs. 6 and 7, respectively. Stock variables of the system are available surface water, available groundwater, per capita industrial water demand, per capita domestic water demand, and population. These stock variables increase or decrease in response to changes in inflow and outflow rate variables. The SFD of agricultural sub-system is not shown here. This SFD would be almost the same as its CLD (Fig. 5) as the only stock variable of this sub-system is water supply.

4.3. Water resources performance indices

Two indices or performance measures are used to illustrate the impacts of different management policies on various sub-systems of the Zayandeh-Rud water resources system. These indices include the reliability and vulnerability of the water supply system. The reliability index is defined as the probability that available water resources can meet the demands during the entire simulation period (Eq. (1)), indicating the long-term capability of the system to provide sufficient water supply (Klemes et al., 1981; Hashimoto et al., 1982):

$$ReI = \frac{\text{Number of years with } D = 0}{N} \quad (1)$$

where D is the water deficit and N is the number of years or the length of the simulation period (McMahon et al., 2006).

The vulnerability index in year i is defined as the expected value of deficits or average annual deficit divided by average annual demand in the deficit period (Eq. (2)), characterizing the average probability of failure of the water resources to meet the water demand (Sandoval-Solis et al., 2011):

$$VuI = \frac{\left(\sum_{i=1}^{N}\right)/(\text{Number of years with } D > 0)}{\text{Water demand}} \quad (2)$$

4.4. Model calibration

The ability of the model to capture the underlying system structure is assessed through behavior reproduction and sensitivity analyses. Once the model is calibrated it can be used to evaluate various water resources management strategies and policies using an annual time step. The spatial boundaries of the model are based on watershed boundaries and the time horizon of the model is 30 years (2011–2040). The hydrological CLD is simulated using data from the period of 1971–2000, assuming that historical hydrologic trends hold into the future. In this model, natural and transferred flows, precipitation, and temperature are input time series data. Evapotranspiration and percolation to groundwater are defined as functions of temperature and precipitation, respectively. Runoff is calculated by SCS curve number method (SCS, 1972) as a function of precipitation and land use. Evaporation from groundwater, natural groundwater inflow, groundwater seepage, and transferred outflow are fixed variables in the model. Initial population and per capita industrial and domestic water demands are set according to the available data for the year 2010. The base capacities of surface water and groundwater withdrawals are set to 2000 and 4000 MCM, respectively, based on the current water consumption levels in the basin (OWWMP, 2010). Water supply data

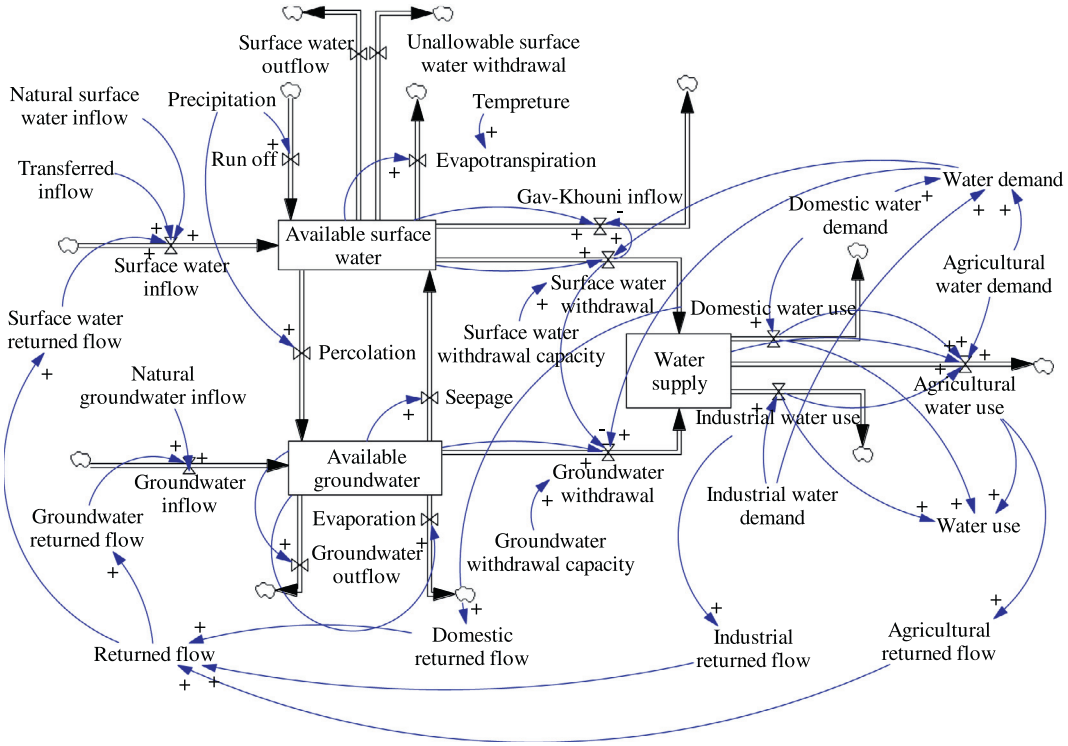

Fig. 6. Stock and flow diagram of the hydrological sub-system.

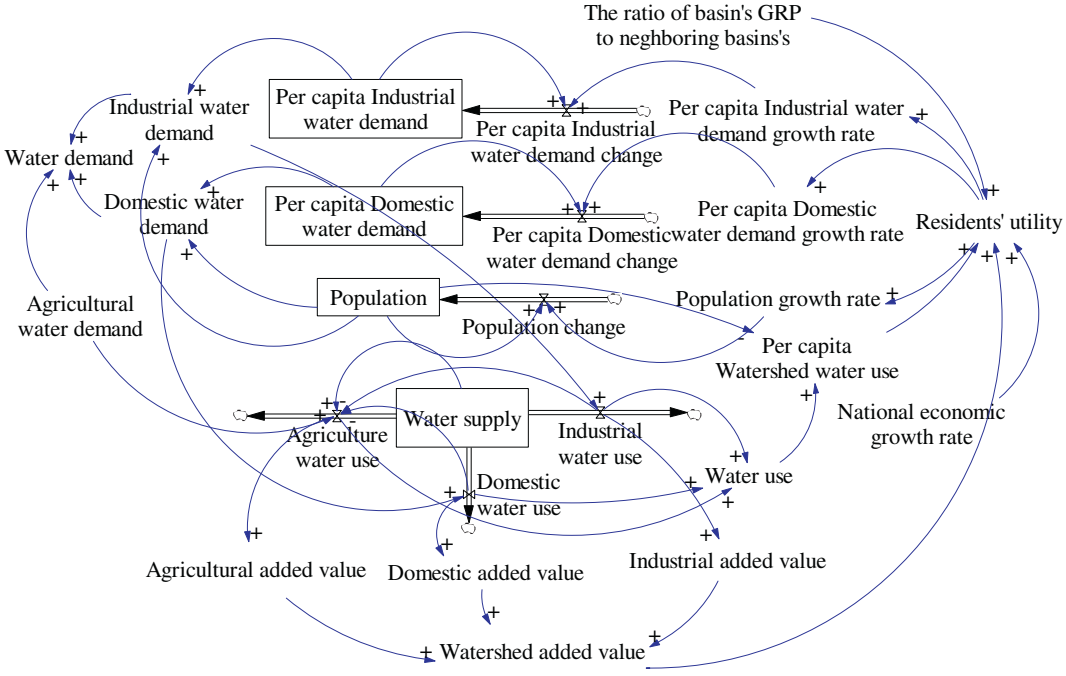

Fig. 7. Stock and flow diagram of the socioeconomic sub-system.

from Iran Ministry of Energy's Office for Water and Wastewater Macro-Planning (OWWMP, 2010) and unpublished data for water allocation and transferred water from Isfahan Regional Water Company were used to characterize groundwater and surface water resources. Likewise, the model uses agricultural data from Jahad Agriculture Ministry, including land area, and prices and production levels of different crops. Information about the meteorological variables and the basin's population were collected from Meteorological Organization and Isfahan Province Management and Planning Organization, respectively.

The observed data for a time period of ten years (2001–2010) is used for calibrating the parameters of the ZRW-MSM 2.0 model. In the first step of calibration, most model variables were kept constant to run simulations without considering dynamic feedbacks within the system. This was necessary to identify critical variables in each sub-system. In the next step, the process of reproducing the

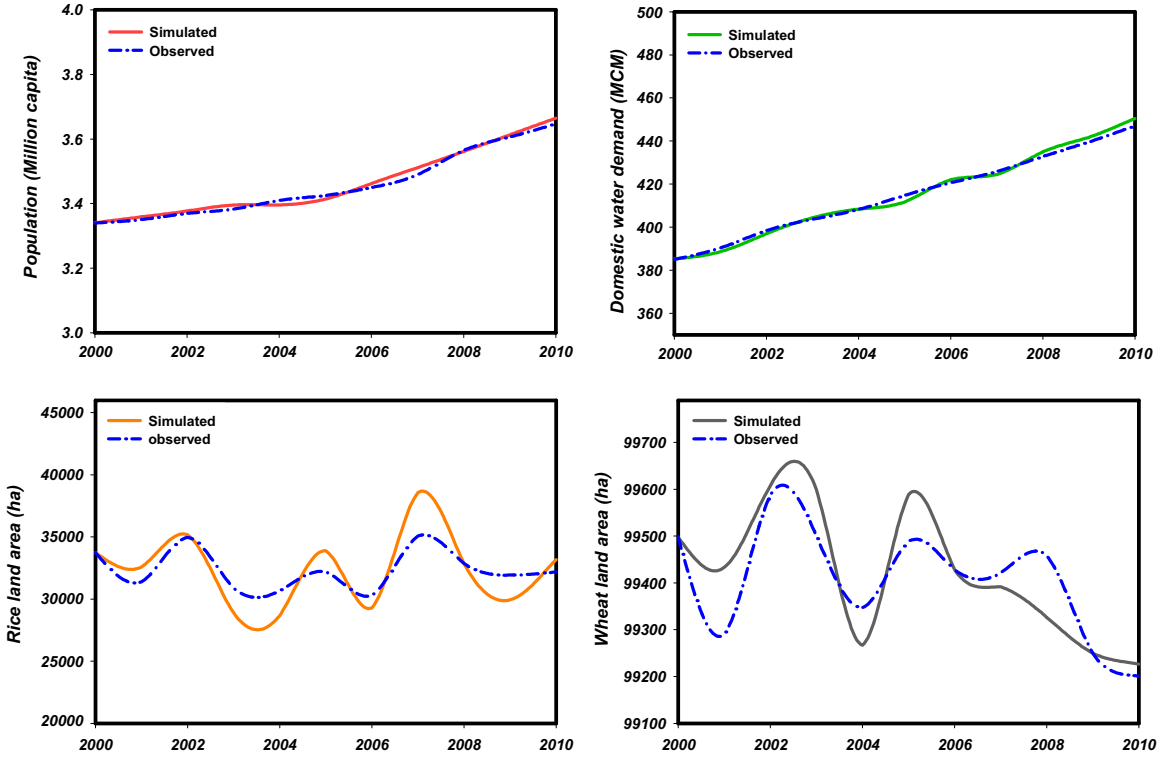

Fig. 8. The comparison of observed data and simulation results.

system's historical trends with dynamic feedbacks was initiated by adjusting some hydrologic and socioeconomic variables. Finally, further modifications of parameters were made by running the model with all feedback loops to mimic the trends of observed behaviors in the basin based on the available historical data. Fig. 8 shows the comparison between the simulated and observed values for population, domestic water demand, and agricultural land area for rice and wheat production over the calibration period. Overall, the correlations between the observed and simulated trends of these parameters are found to be acceptable for a complex integrated model, indicating that the model has been satisfactorily calibrated to reproduce the behavior of different parameters within the system.

5. Model application

The model is used in a two-step procedure to provide insights into the most effective strategies and policies to improve water resources management in the Zayandeh-Rud River Basin. In the first step, different water resources management strategies are adopted to identify policy leverage areas. In the second step, a more focused analysis is performed to develop suitable water management policies with reference to the identified leverage areas.

5.1. Strategy identification

Sensitivity analyses using extreme conditions provide insights into effective strategies for water resources management during the period of 2010–2040. The developed model is run under extreme hypothetical socioeconomic and water management scenarios (Table 4) to identify the key drivers of the system. Fig. 9 shows the behavior of selected model variables throughout the simulation period. Under the population control scenario (P.C.) where population and domestic water demand do not change, episodes of severe water shortage along are simulated in the basin due to increasing industrial agricultural water demands. The economic recession scenario is simulated by applying constant population and industrial and domestic water demands, and low level of residents' utility. The model simulates great water shortage (in the agricultural sector), which is approximately similar to P.C. scenario. In the case of industrial watershed (I.W.), the residents' utility rises throughout the simulation period in response to industrialization and more economic activities. Watershed population and domestic and industrial water demands increase as compared with previous scenarios while no significant water shortage is projected. Under no surface water withdrawal (N.S.W.W.) the residents' utility declines continuously over simulation period due to decreasing water supply. Water shortage grows as population and domestic and industrial water demands increase with decreasing growth rate. In the case of no groundwater withdrawal (N.G.W.W.) low values are simulated for residents' utility (lower than P.C.). Watershed population and domestic and industrial water demands increase with lower growth rate than N.S.W.W. However, the projected water shortage is more severe than the case of N.S.W.W. due to greater unmet agricultural water demand.

Table 4
Extreme socioeconomic and water management scenarios for strategy identification.

Scenario	Description
Population control (P.C.)	Population and domestic water demand are assumed to be constants after 2010
Economic recession (E.R.)	Residents' utility is set equal to zero
Industrial watershed (I.W.)	Agricultural water use is set equal to zero
No surface water withdrawal (N.S.W.W.)	Surface water withdrawal is assumed to be zero
No groundwater withdrawal (N.G.W.W.)	Groundwater withdrawal is assumed to be zero

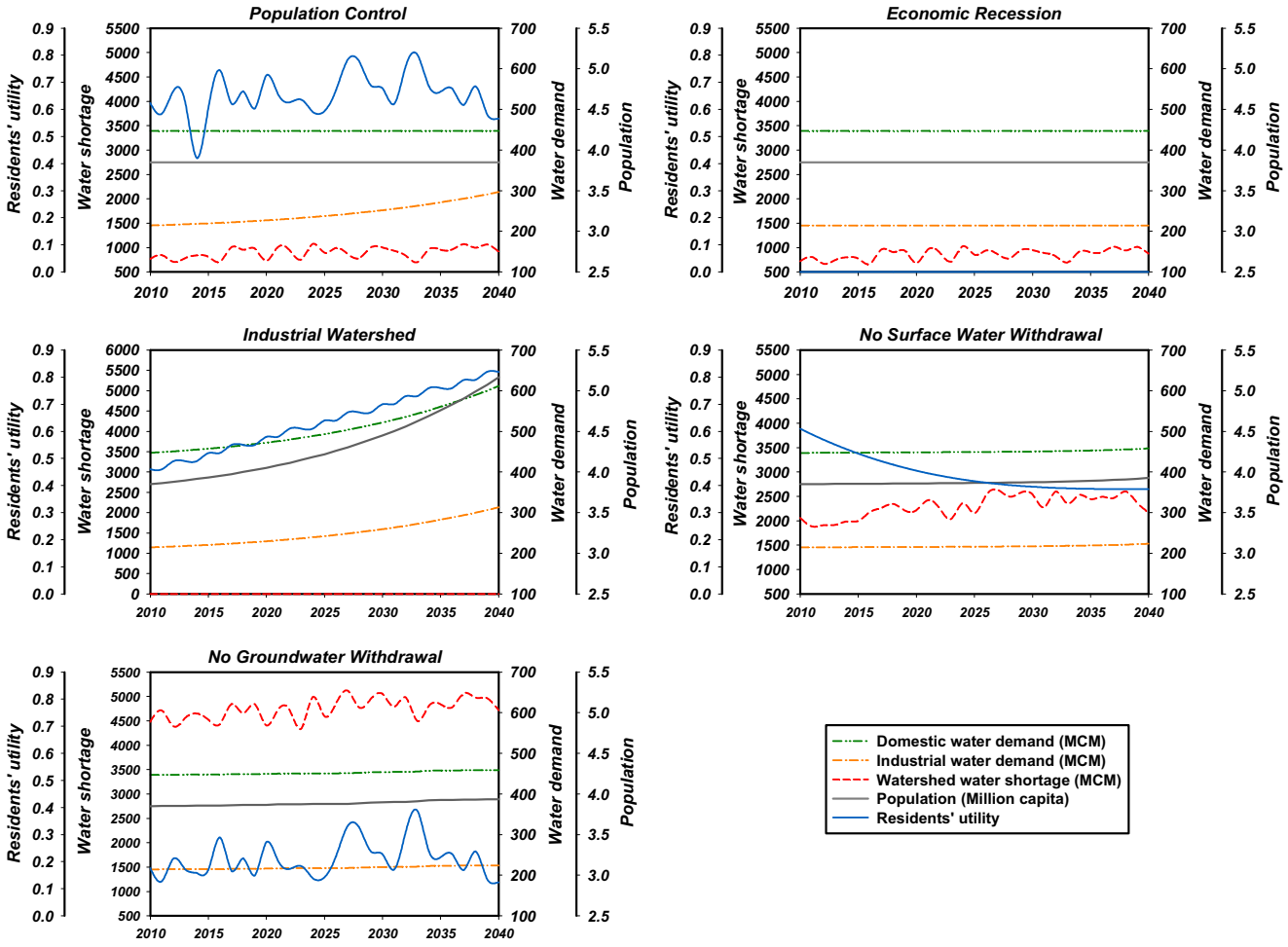

Fig. 9. Behavior of selected model variables in the simulation period (2010–2040) under extreme socioeconomic and water management scenarios.

The response of the Zayandeh-Rud water resource system to the extreme scenarios, as illustrated in Fig. 9, are examined by analyzing the behaviors of main variables of hydrological, socioeconomic, and agricultural sub-systems, as well as reliability and vulnerability indices. Table 5 presents the results and Table 6 summarizes the corresponding reliability and vulnerability indices for different water sectors. Unlike domestic and industrial demands, the vulnerability index of agricultural demand is high (Table 6), indicating that agricultural water use is the major driver of water shortage in the basin. Agricultural water demand remains very high even under the economic recession scenario in which an extreme undesirable socioeconomic condition is simulated by setting residents' utility equal to zero. The highest vulnerability indices, however, are calculated for environmental flow of Gav-Khouni Marsh. The same finding is reflected in reliability index calculations where agricultural water deficit persists throughout the simulation period. Maximum reliability index of 1 is calculated for domestic and industrial uses under different extreme scenarios. The reliability of environmental flows is highest under the extreme cases of using water only for industrial economic activities or when no surface water is withdrawn. The results suggest that proper management of agricultural water should take higher priority over improving the patterns of domestic and industrial water uses because efficiency of water use in this sector can, in effect, mitigate water tension in the basin during the simulation period. Similarly, managing domestic water demand will be more important for relieving water stress than industrial water demand. Furthermore, dependence of the residents' utility on groundwater resources is greater than surface water resources. The analysis determines that agricultural water demand management and groundwater management, which supply agricultural water, are the key water resources management strategies in the basin.

5.2. Policy analysis

Using the understanding of policy levers and responses, effective policies to improve the long-term performance of the system can be developed. This phase of the analysis involves trial and error, as well as some speculations about effectiveness of different policies. Good expert judgment can minimize the number of scenarios to be tested. Nevertheless, a good number of simulations are required to identify the best policy options for the basin. Here, a number of agricultural water and surface water management policies have been analyzed based on the results of the identified strategies. Descriptions of selected policy simulation scenarios are summarized in Table 7. Each policy is defined by changing one or more parameter(s) of the model to represent, for example, likely changes in water withdrawals from surface and groundwater resources, agricultural water use efficiency, and agricultural crop choice.

The simulated trends for selected variables of the system are shown in Figs. 10 and 11. The simulation results for the business as usual (B.a.U.) scenario are provided as a reference for comparison. Under this scenario population and industrial and domestic

Table 5
Explanation of simulation results under extreme socioeconomic and water management scenarios.

Scenario	Output description
Population control (P.C.)	Domestic water demand does not change due to population control; industrial water demand increases in the simulation period; great agricultural water shortage in the whole period (reliability index is equal to zero and vulnerability index is high); Gav-Khouni Marsh receives no water except for a few years due to high amounts of rainfall (vulnerability index is high); severe water shortage is seen in the basin
Economic recession (E.R.)	Agricultural water demand is very high and cannot be satisfied (reliability and vulnerability indices are approximately similar to P.C.); Gav-Khouni Marsh receives no water except for a few years due to high amounts of rainfall (reliability and vulnerability indices are approximately similar to P.C.); water shortage does not change significantly in comparison with P.C.
Industrial watershed (I.W.)	Residents' utility rises through the whole period; population, domestic, and industrial water demands increase with increasing growth rates; Gav-Khouni Marsh receives sufficient water in the simulation period (reliability and vulnerability indices are 1 and zero, respectively); no water shortage is expected in the basin
No surface water withdrawal (N.S.W.W.)	Residents' utility drops continuously; population, domestic, and industrial water demands increase with decreasing growth rate; agricultural water use is lower than I.W. and decreases during the simulation period; vulnerability index for agriculture is very higher than P.C.; Gav-Khouni Marsh is provided with enough water to sustain in the simulation period (reliability and vulnerability indices are similar to I.W.); growing water shortage is expected in the basin (greater water tension than P.C.)
No groundwater withdrawal (N.G.W.W.)	Residents' utility is less than other scenarios; population, domestic, and industrial water demands increase with lower growth rate than N.S.W.W.; agricultural water use is very lower than N.S.W.W. (vulnerability index for agriculture is more than N.S.W.W.); Gav-Khouni Marsh receives no water in the simulation period (vulnerability index is lower than P.C); greater water tension than N.S.W.W.

Table 6
Reliability and vulnerability of different water sectors under extreme socioeconomic and water management scenarios.

Scenario	ReI (agriculture)	ReI (environment)	ReI (domestic and industrial)[a]	VuI (agricultural)	VuI (environmental)	VuI (domestic and industrial)[b]
Population Control (P.C.)	0.00	0.10	1.00	0.28	0.87	0.00
Economic Recession (E.R.)	0.00	0.10	1.00	0.23	0.87	0.00
Industrial Watershed (I.W.)	–	1.00	1.00	–	0.00	0.00
No Surface Water Withdrawal (N.S.W.W.)	0.00	1.00	1.00	0.54	0.00	0.00
No Groundwater Withdrawal (N.G.W.W.)	0.00	0.00	1.00	0.89	0.99	0.00

[a,b] Domestic and industrial water demands are satisfied based on the current allocation policy in the basin. Therefore, the values of reliability and vulnerability indices are equal to 1 and zero respectively under different scenarios.

Table 7
Description of selected water management policies.

Policy scenario	Description
Business as usual (B.a.U.)	Transferred inflow and outflow are assumed to be similar to current watershed plans; surface water withdrawal capacity is equal to 2000 MCM; groundwater withdrawal capacity is equal to 4000 MCM; agricultural water use efficiency is equal to 45%
Agricultural water demand management I (A.W.D.M.I)	Water transfer similar to B.a.U.; surface water and groundwater withdrawals remain constant; agriculture water use efficiency is 80%
Agricultural water demand management II (A.W.D.M.II)	Water transfer similar to B.a.U.; surface water and groundwater withdrawals remain constant; agriculture water use efficiency is 45%; alfalfa, corn and rice are not cultivated in the basin
Agricultural water demand management III (A.W.D.M.III)	Water transfer similar to B.a.U.; surface water and groundwater withdrawals remain constant; agriculture water use efficiency is equal to 45%; alfalfa, corn, rice, barley and vegetable are not cultivated in the basin
Inter-basin water transfer (I.W.T)	Surface water inflow increases due to the operations of Goukan Tunnel (2015), Kuhrang Tunnel No. 3 (2016), and Beheshtabad Tunnel (2020) inter-basin water transfer with 200, 100, and 500 MCM capacities respectively; surface water withdrawal capacity increases linearly, getting 1000 MCM in 2020 more than its current amount in 2015; groundwater withdrawal capacity increases non-linearly up to 4500 MCM in 2040; agricultural water use efficiency is equal to 45%
Inter-basin water transfer and demand management (I.W.T.D.M.)	Increase in surface water inflow same as I.W.T.; surface water and groundwater withdrawals remain constant; agricultural water use efficiency is 80%; alfalfa, and rice are not cultivated

water demands increase over the simulation period. Severe water shortage is expected due to high agricultural water demand and environmental water shortages, which will cut off Gav-Khouni Marsh's inflow. The first agricultural water demand management scenario (A.W.D.M.I) projects smaller population growth rate, and domestic and industrial water demands as compared with B.a.U. Lower agricultural water demand is expected due to improved irrigation efficiency, and the simulated water shortage lower than B.a.U. The Gav-Khouni receives adequate inflows only for a few years. Under the second agricultural water demand management scenario (A.W.D.M.II), lower residents' utility leads to smaller increase in industrial and domestic water demands and population than B.a.U. and A.W.D.M.I. The agricultural water demands are satisfied for a few years of the simulation period and water shortage is low in other years due to cultivation of water-efficient crops. Compared to A.W.D.M.I the Gav-Khouni Marsh's inflow improves only slightly. The simulation of the third agricultural water demand management scenario (A.W.D.M.III) results in the lowest levels of residents' utility over the simulation period. The increase in population, industrial, and domestic water demands are considerably lower than the other strategies. No agricultural water shortage is expected because of reduced cultivated land area, and the water

shortage is expected to be lower than that of A.W.D.M.II. The Gav-Khouni Marsh's average annual inflow (~150 MCM) is sustained more than 50% of the time (Fig. 11).

The inter-basin water transfer scenario (I.W.T.) results in the highest residents' utility along with higher growth rates for population and industrial and domestic water demands (Fig. 10). Water shortage is expected to reduce after increase in surface water supply, but increasing water demand causes water shortage to reappear. Agricultural water demand rises significantly after completion of the third planned water transfer project (Beheshtabad Tunnel). As for environmental flows, the Gav-Khouni Marsh receives sufficient water after completion of the water transfer projects, but its inflow declines toward the end of the simulation period (Fig. 11). Interestingly, the simulated end-of-period water shortage in the basin under I.W.T. is higher than B.a.U. The last policy scenario is inter-basin water transfer and demand management (I.W.T.D.M.), which projects a lower growth rate for increase in population, and industrial and domestic water demands than I.W.T. (Fig. 10). Under this scenario, agricultural water demand is expected to be lower than B.a.U due to change in crop pattern and improved irrigation efficiency. No agricultural water shortage is projected after the operation of Goukan Tunnel in 2016, while Gav-Khouni Marsh receives sufficient water (Fig. 11) after completion of Beheshtabad Tunnel. This scenario addresses the basin's water shortage over the three-decade planning horizon.

The behavioral trends of the main variables in the watershed system under the simulated management policies are explained in Table 8. Table 9 presents the values of reliability and vulnerability indices for different sectors under the selected management scenarios. Overall, the results suggest that in the absence of appropriate management policies the basin's water shortage will exacerbate with time. Improving the efficiency of agricultural water use (A.W.D.M.I) is the most critical policy, although it may not be a definitive solution for sustainable water resources management in the basin. Rehabilitation and modernization of the basin's irrigation systems can decrease agricultural water demand and use, reducing required water supply. But, the simulated water shortage shows that this policy will not obviate water shortage altogether. The results of A.W.D.M.II and A.W.D.M.III show that cropping change to water-efficient crops (e.g., garden productions, potato, onion, and cereal) and the reducing cultivated land area can most considerably decrease agricultural water demand. The simulated water supply under modified crop pattern can approximately provide sufficient water for agricultural section and Gav-Khouni

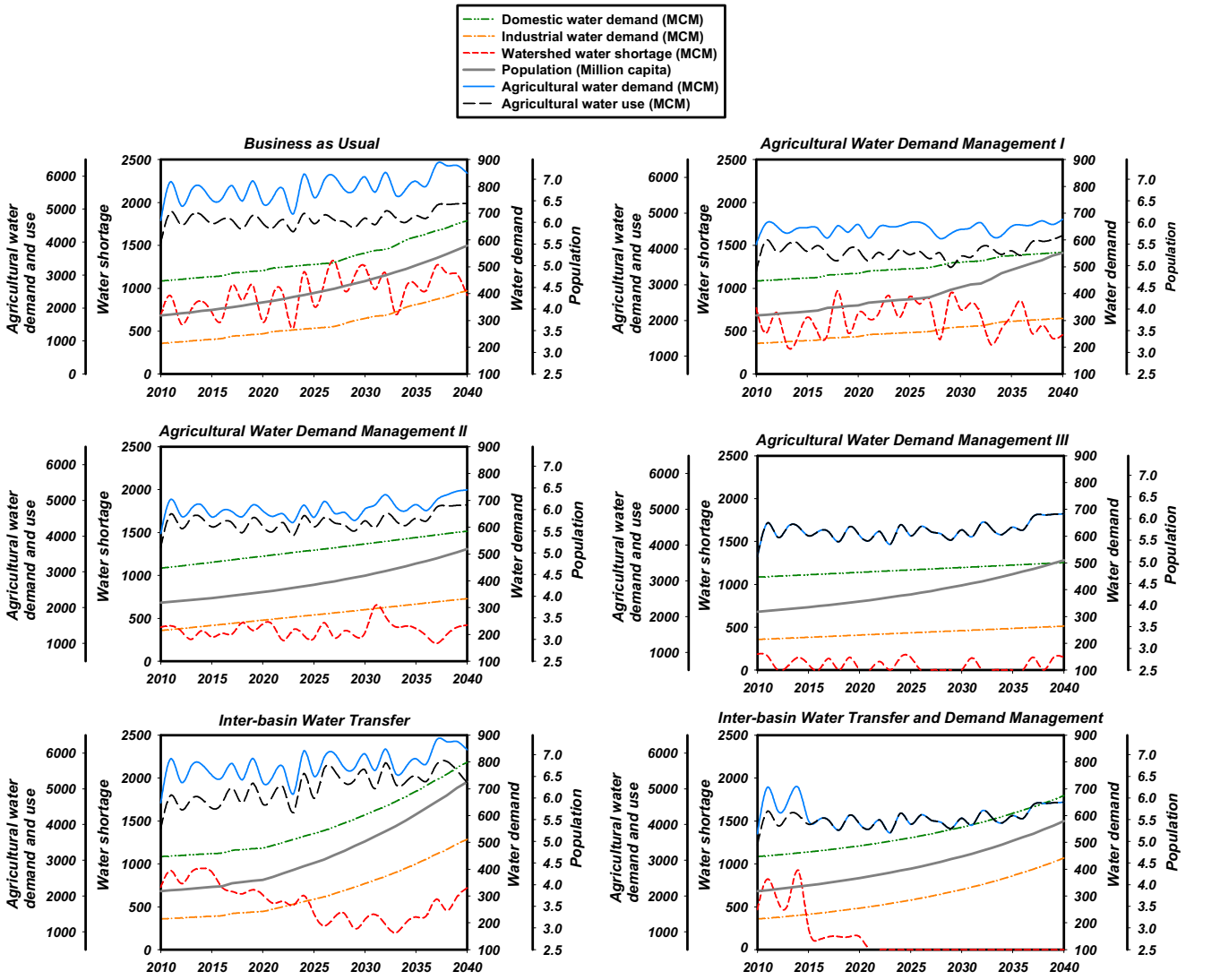

Fig. 10. Behavior of selected model variables in the simulation period (2010–2040) under different policy scenarios.

Marsh. Implementation of water transfer projects (I.W.T.) raises surface water supply, reducing water shortage in the short-run. However, increasing water demand causes more severe water shortage than B.a.U. at the end of simulation period due to higher resident's utility, leading to more groundwater withdrawal to supply sufficient water for the basin's water uses. Supplying more water using inter-basin water transfer (I.W.T.) is a band-aid solution that can temporarily ease the water scarcity while exacerbating the situation in the long-run. The results for the I.W.T.D.M policy indicate that increased water supply coupled with demand management is the most reasonable method for mitigating water scarcity in the basin. The controlled economic development and population growth, as a result of lower resident's utility than I.W.T., can address water shortage after completion of the planned water transfer projects.

6. Discussion

Models are simplified representations of real systems (Box and Draper, 1987; Sterman, 2000) and ZRW-MSM 2.0 is no exception. However, despite their simplifications, models can provide valuable insights as long as their limitations are not overlooked when interpreting their results for policy making (Madani, in press). Some parameters of the integrated models (e.g., sociopolitical attributes) may be prohibitively difficult to quantify, especially in system dynamics models. A number of simplifying assumptions were necessary to characterize the supply-oriented water management in the Zayandeh-Rud River Basin. Interaction between surface and groundwater, i.e. percolation and seepage, has been simulated linearly in the hydrological sub-system. Furthermore, this component of the model represents groundwater resources in a lumped fashion whereas, in reality, over twenty tow aquifers with different withdrawals and hydrostatic storage capacities have been identified in the basin. In the agricultural sub-system, it is assumed that the dynamic market of each crop is independent from the others while dependence may be seen in real markets or cultivation of different crops. The developed agricultural CLD considers only ten major crops to represent the variety of different crops in the basin. Finally, the ratio of the basin's GRP relative to neighboring basins is defined as a constant value, which limits characterization of socio-economic dynamics. In the face of these simplifying assumptions,

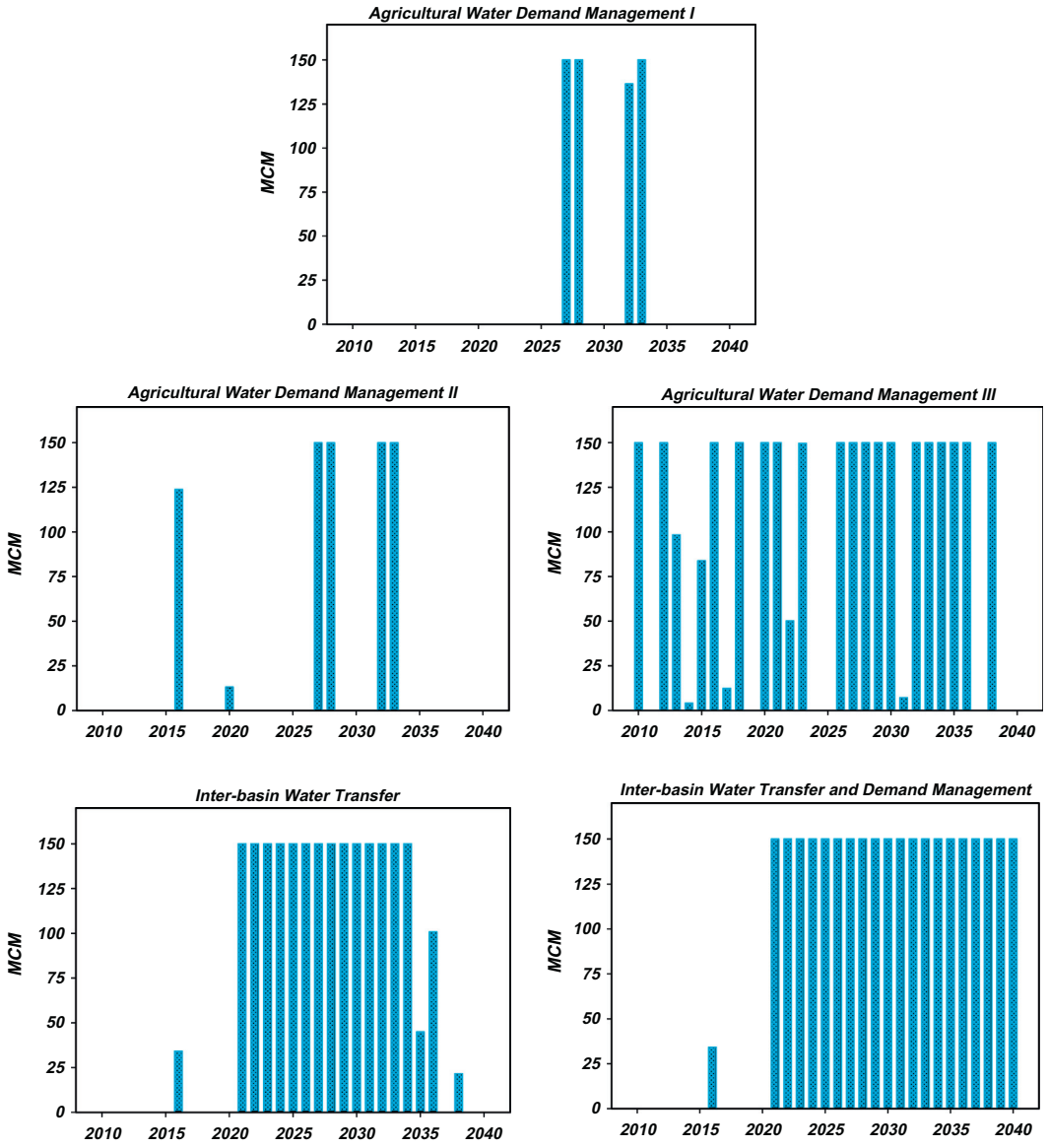

Fig. 11. Gav-Khouni inflow in the simulation period (2010–2040) under different management policies. The average annual flow requirement to sustain Gav-Khouni Marsh is ~150 MCM, whereas under business as usual the wetland receives no inflow.

Table 8
Description of the main variables' behavior under different management policies.

Management policy	Description of outputs
Business as usual (B.a.U.)	Industrial and domestic water demands increase; population and watershed water demand increase with high growth rate; severe agricultural and environmental water shortages are expected throughout the simulation period according to the vulnerability and reliability indices; extra groundwater withdrawal continues due to severe water tension; Gav-Khouni Marsh receives no water in the whole period (reliability and vulnerability indices are 1 and 0, respectively)
Agricultural water demand management I (A.W.D.M.I)	Increase in industrial and domestic water demands and population are lower than B.a.U.; agricultural water shortage is lower than B.a.U. in the whole period, according to the vulnerability index; Gav-Khouni Marsh receives no water except for a few years due to high rainfall
Agricultural water demand management II (A.W.D.M.II)	Increase in industrial and domestic water demands and population are lower than B.a.U. and A.W.D.M. I due to lower residents' utility; groundwater withdrawal and water shortage are considerably lower than B.a.U and A.W.D.M. I; agricultural water demand is satisfied for a few years and water shortage is low in other years according to the vulnerability index; Gav-Khouni Marsh receives no water in the whole period except for a few years
Agricultural water demand management III (A.W.D.M.III)	Increase in industrial and domestic water demands, and population are considerably lower than the other scenarios due to significantly lower residents' utility; groundwater withdrawal is smaller than A.W.D.M. II due to reduced agricultural water demand; no agricultural water shortage in the simulation period according to the vulnerability and reliability indices; Gav-Khouni Marsh is not supplied with sufficient water about 60% of the time
Inter-basin water transfer (I.W.T)	Increase in industrial and domestic water demands and population are much higher (exponential growth) than the other policies after increase in surface water inflow; agricultural water demand increases after completion of Beheshtabad Tunnel; more groundwater withdrawal occurs to meet high water demand at the end of the simulation period (as a result of high resident's utility); the values of vulnerability indices for agriculture and environment are lower than B.a.U.; Gav-Khouni Marsh receives sufficient water after completion of water transfer projects, but no water at the end of simulation period (reliability index is higher than B.a.U); water shortage in the basin is higher than B.a.U. at the end of simulation period
Inter-basin water transfer and demand management (I.W.T.D.M.)	Industrial and domestic water demands and population increase with lower growth rates than I.T.W.; no agricultural water shortage after the operation of Goukan Tunnel in 2016; Gav-Khouni Marsh receives sufficient water after completion of Beheshtabad Tunnel; vulnerability indices for agriculture and environment are lower than I.T.W., while their reliability indices are higher than I.T.W.; no water shortage is expected after increase in surface water inflow

Table 9
Reliability and vulnerability of different water sectors under different management policies.

Scenario name	ReI (agriculture)	ReI (environment)	ReI (domestic and industrial)[a]	VuI (agriculture)	VuI (environment)	VuI (domestic and industrial)[b]
Business as usual (B.a.U.)	0.00	0.00	1.00	0.23	1.00	0.00
Agricultural water demand management I (A.W.D.M.I)	0.00	0.10	1.00	0.15	0.87	0.00
Agricultural water demand management II (A.W.D.M.II)	0.00	0.13	1.00	0.08	0.84	0.00
Agricultural water demand management III (A.W.D.M.III)	1.00	0.53	1.00	0.00	0.36	0.00
Inter-basin water transfer (I.W.T)	0.00	0.47	1.00	0.13	0.50	0.00
Inter-basin water transfer and demand management (I.W.T.D.M.)	0.80	0.67	1.00	0.10	0.35	0.00

[a,b] Domestic and industrial water demands are satisfied based on the current allocation policy in the basin. Therefore, the values of reliability and vulnerability indices under different scenarios are equal to 1 and zero respectively.

ZRW-MSM 2.0 facilitates investigation of the trends of behavior as opposed to quantitative snapshots of the system behavior, essential for generating insights into big-picture, long-term path of the system under different policy scenarios (Madani and Mariño, 2009; Mirchi et al., 2012).

Understanding the system's governing archetypal behavior can provide insights for balancing water resources management and development. System archetypes are generic CLDs that are used as diagnostic tools to identify and address problematic dynamic behavior (Senge, 1992; Braun, 2002; Wolstenholme, 2003). Braun (2002) describes common system archetypes and their corresponding behaviors, including Limits to Growth, Shifting the Burden, Eroding Goals, Escalation, Success to the Successful, Tragedy of the Commons, Fixes that Backfire (or Fixes that Fail), Growth and Underinvestment, Accidental Adversaries, and Attractiveness Principle. Some of these archetypes can be used to explain different aspects of the basin's water resources management (Mirchi et al., 2012). For example, the basin's socioeconomic development in a water-deficient region is essentially governed by the Limits to Growth archetype. The water scarcity is only the symptom of a more profound problem, that is exceedance of natural supply capacity of water resources in the basin. Similarly, the basin's success in securing additional water resources in a potentially competitive setting can be explained by the Success to the Successful archetype, where the system's growth as compared with competitors enables it to secure even more resources for growth. Within the basin's agricultural sector the competition over groundwater triggers significant drawdown of groundwater table as governed by the Tragedy of the Commons.

From a management perspective, however, the Zayandeh-Rud River Basin's recurring water shortage has the characteristics of the Fixes that Backfire archetype (Fig. 12). The theory of Fixes that Backfire archetype states that short-sighted solutions that relieve the symptoms of a problem without addressing the root causes create a weak balancing loop that will entail unintended consequences. The quick fix solution triggers a stronger reinforcing loop, which causes the problem to re-erupt in the future in an aggravated form, often with challenging unintended consequences (Fig. 12). The main driver of the Zayandeh-Rud Basin's water shortage is the unfettered development, which leads to increased demand, causing water scarcity to reappear in an exacerbated form (Fig. 13). Therefore, increasing water supplies through water

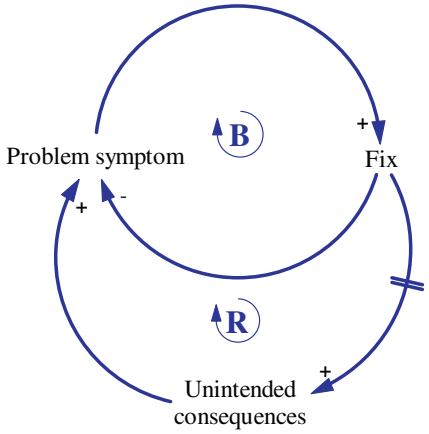

Fig. 12. Fixes that Backfires system archetype.

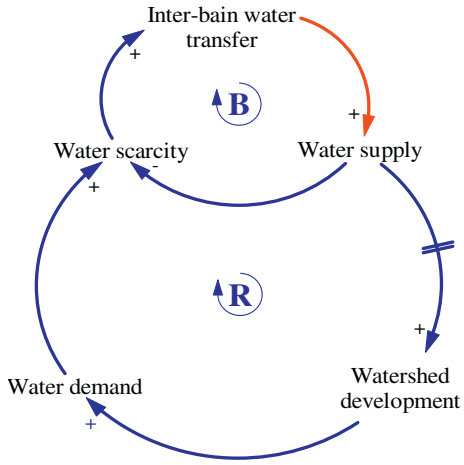

Fig. 13. The main loops of the water resources system of the Zayandeh-Rud River Basin.

transfer projects are merely quick fixes that are doomed to create challenging side-effects in a parched region where water is the main engine for development. The simulation results of ZRW-MSM 2.0 indicate that the basin will experience a dramatic and growing water shortage if current local water resources management policies are used in the future without necessary modifications and adaptations. The persistent water shortage is mainly due to presence of an unaddressed reinforcing feedback loop that creates a vicious supply-development-demand cycle (Fig. 13).

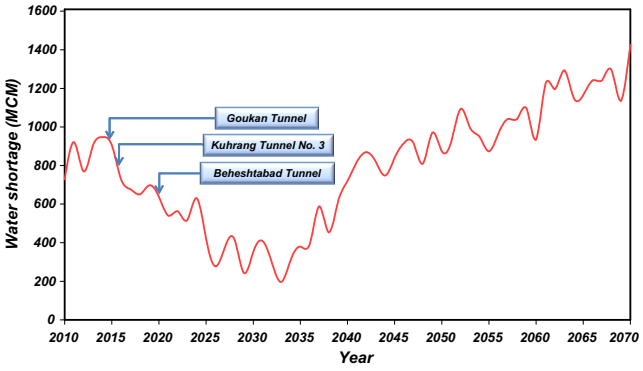

Fig. 14. The projected trend of water scarcity in the basin over time.

The model predicts failure and depletion of the basin's water resources by mid next century if the current water supply trends hold into the future.

Despite the inadequacy of water transfers as a sustainable solution to the water shortage problems, three additional inter-basin water transfer projects are currently under development to satisfy the increasing water demand in the basin. While these projects may be necessary given the reality and severity of current water scarcity, supplying more water without effective demand management schemes will create the false perception of development potential in the basin (Madani and Mariño, 2009). This false message can promote watershed development and attract more people to settle down in the basin, expanding a community that is growing much beyond what water resources can support naturally. In the long run, continuous watershed development and population growth, due to in-migration, will increase water demand, intensifying water scarcity. Fig. 14 illustrates that supplying more water to the basin through water transfer will decrease water scarcity in the short run (decreasing trend of water shortage). However, an increasing trend of water scarcity in the long run indicates that watershed development and population growth will increase water demand, intensifying water scarcity. Thus, the problem will continue to reappear more severely as has been the case in the past, as the residents' expectation of higher utility places more pressure on water managers to endorse development of more water-transfer projects.

During the past 60 years, the time interval between the water resources development and full allocation of the added water supply in the basin has been short. There is a vital need to shift away from water supply-oriented to water demand management policies for managing the water shortage in the basin. Emphasis should be placed on effective strategies and policies for managing the watershed development and water demand simultaneously. System-wide demand management programs that aim at increasing awareness about the water scarcity situation must become integral components of the basin's water resources management, improving the effectiveness of the current and planned inter-basin transfers. Although not a permanent solution, cultivating water-efficient crops and improving the irrigation efficiency is the most critical policy leverage area to decrease the agricultural water use and, subsequently, agricultural water shortage. The favorability of this policy is manifest in higher reliability and lower vulnerability within the system as compared to current practices (Table 9).

7. Conclusions

Water resources decision making should be based on a holistic view of the problems due to the multitude of complex, interlinked socio-economic and bio-physical sub-systems within watershed systems. The recognition of various feedback mechanisms within a water resource system is important for appropriate quantitative and/or qualitative projection of long-run behavior. System dynamics is a practical framework for understanding water resource systems' underlying structures, and capturing main feedback loops in an integrated fashion. The approach offers convenient tools such as CLDs and SFDs that facilitate conceptualization of water resource systems, providing a basis for quantitative simulation in order to examine different policy options. Although quantitative characterization of large water resources systems can be difficult, and sometimes speculative, due to complexity of interdependent subsystems, the approach provides a practical means for identifying plausible behavioral trends that can guide policy making.

The traditional management approach for handling the Zayandeh-Rud River Basin's persistent water scarcity problem has the properties of the Fixes that Backfire system archetype. The

supply-oriented management scheme through inter-basin water transfers relieves the symptom of a larger problem only temporarily. The more critical problem is the unfettered development and inefficient agricultural practices that has caused the Zayandeh-Rud system to reach, and move beyond, the natural supply capacity of groundwater and surface water resources. Soon after completion of each water transfer project, the water scarcity reappears due to continuous development and in-migration intensified by a false perception of water availability. The problem becomes more challenging if the long-term socioeconomic vulnerability and damage of ecosystems are taken into account. As the most important policy lever, water resources and agricultural managers in Zayandeh-Rud River Basin, and similar areas in Iran, are urged to focus on increasing the efficiency of agricultural water use and promoting the cultivation of water-efficient crop types to ensure highest reliability and lowest vulnerability within the system. The simulation results of ZRW-MSM 2.0 demonstrate that the inter-basin water transfer alone is an unsustainable solution to the basin's water scarcity problem. Thus, it is critical to implement system-wide demand management programs to increase the effectiveness of the current supply-oriented approach by improving the balance between socioeconomic development and water resources supply.

Acknowledgments

This paper was written during the first author's stay at the University of Central Florida (UCF) as a visiting scholar. The first author would like to thank the Iran's Ministry of Science, Research and Technology (MSRT) and Isfahan University of Technology, for financial support during his stay at UCF. Special thanks go to the Hydro-Environmental and Energy Systems Analysis (HEESA) Research Group at UCF for hospitality and their extensive support during this research. The authors acknowledge valuable comments and suggestions from two anonymous reviewers.

References

Abrishamchi, A., Tajrishi, M., 2005. Inter-basin water transfer in Iran. In: Water Conservation, Reuse, and Recycling, Proceeding of an Iranian American workshop. The National Academies Press, Washingon, DC, pp. 252–271.

Ahmad, S., Prashar, D., 2010. Evaluating municipal water conservation policies using a dynamic simulation model. Water Resour. Manage. 24 (13), 3371–3395.

Ahmad, S., Simonovic, S.P., 2000. System dynamics modeling of reservoir operations for flood management. J. Comput. Civ. Eng. 14 (3), 190–198.

Ahmad, S., Simonovic, S.P., 2004. Spatial system dynamics: a new approach for simulation of water resources systems. J. Comput. Civ. Eng. 18 (4), 331–340.

Allan, T., 2003. IWRM/IWRAM: a new sanctioned discourse? SOAS Water Issues Study Group Occasional Paper 50. SOAS/King's College, London.

Andrade, J.G.P.D., Barbosa, P.S.F., Souza, L.C.A., Makino, D.L., 2011. Interbasin water transfers: the Brazilian experience and international case comparisons. Water Resour. Manage. 25 (8), 1915–1934.

Bagheri, A., Hjorth, P., 2007. A framework for process indicators to monitors for sustainable development: practice to an urban water system. Environ. Dev. Sustain. 9 (2), 143–161.

Bagheri, A., Darijani, M., Asgari, A., Morid, S., 2010. Crisis in urban water systems during the reconstruction period: a system dynamics analysis of alternative policies after 2003 earthquake in Bam – Iran. Water Resour. Manage. 24 (11), 2567–2596.

Ballestero, E., 2004. Inter-basin water transfer public agreement: a decision approach to quantity and price. Water Resour. Manage. 18 (1), 75–88.

Bender, M.J., Simonovic, S.P., 1996. A systems approach for collaborative decision support in water resources planning. In: Proceeding of International Symposium on Technology and Society Technical Expertise and Public Decisions. IEEE Princeton, pp. 357–363.

Box, G.E.P., Draper, N.R., 1987. Empirical Model-building and Response Surfaces. John Wiley, New York.

Braun, W., 2002. The System Archetypes. <http://wwwu.uni-klu.ac.at/gossimit/pap/sd/wb_sysarch.pdf> (accessed 26.05.12).

Cai, X.M., McKinney, D.C., Rosegrant, M.W., 2003. Sustainability analysis for irrigation water management in the Aral Sea region. Agric. Syst. 76 (3), 1043–1066.

Connell-Buck, C.R., Medellin-Azuara, J., Lund, J.R., Madani, K., 2011. Adpting California's water system to warm vs. dry climates. Clim. Changes 109 (Suppl. 1), S133–S149.

Convention of Wetlands, 1971. The Ramsar Convention of Wetlands. Ramsar, Iran. <http://ramsar.org>.

Davies, E.G.R., Simonovic, S.P., 2011. Global water resources modeling with an integrated model of the social-economic-environmental system. Adv. Water Resour. 34 (6), 684–700.

Draper, A.J., Jenkins, M.W., Kirby, K.W., Lund, J.R., Howitt, R.E., 2003. Economic-engineering optimization for California water management. J. Water Resour. Plann. Manage., ASCE 129 (3), 155–164.

Dyrnes, G.V., Vatn, A., 2005. Who owns the water? A study of a water conflict in the Valley of Ixtlahuaca, Mexico. Water Policy 7 (3), 295–312.

English, P.W., 1968. The origin and spread of qanats in the old world. Proc. Am. Philos. Soc. 12 (3), 170–181.

Evans, M.I., 1994. Important Bird Areas in the Middle East. Bird Life International, Cambridge, United Kingdom.

Ford, A., 1996. Testing the snake river explorer. Syst Dyn Rev 12 (4), 305–329.

Ford, A., 1999. Modeling the Environment: An introduction to system dynamics modeling of Environmental Systems. Island Press, Washington DC, p. 401.

Forrester, J.W., 1961. Industrial Dynamics. MIT Press, Cambridge.

Forrester, J.W., 1969. Urban Dynamics. MIT Press, Cambridge.

Gastelum, J.R., Valdes, J.B., Stewart, S., 2009. A decision support system to improve water resources management in the Conchos Basin. Water Resour. Manage. 23 (8), 1519–1548.

Gichuki, F., McCornick, P.G., 2008. International experiences of water transfers: relevance to India. In: Proceedings of the Workshop on Analyses of Hydrological, Social and Ecological Issues of the NRLP. New Delhi, India, pp. 345–370.

Gleick, P.H., 1998. Water in crisis: paths to sustainable water use. Ecol. Appl. 8 (3), 571–579.

Gohari, A., Eslamian, S., Abedi-Koupaei, J., Massah Bavani, A., Wang, D., Madani, K., 2013. Climate change impacts on crop productivity in Iran's Zayandeh-Rud River Basin. Sci. Total Environ. 442 (1), 405–419.

Growns, I., Reinfelds, I., Williams, S., Goade, G., 2009. Longitudinal effects of a water supply reservoir (Tallowa Dam) on downstream water quality, substrate and riffle macroinvertebrate assemblages in the Shoalhaven River, Australia. Mar. Freshwater Res. 60 (6), 594–606.

Guo, H.C., Liu, L., Huang, G.H., Fuller, G.A., Zou, R., Yin, Y.Y., 2001. A system dynamics approach for regional environmental planning and management: a study for the Lake Erhai Basin. Environ. Manage. 61 (1), 93–111.

Gupta, J., van der Zaag, P., 2008. Interbasin water transfers and integrated water resources management: where engineering, science and politics interlock. Phys. Chem. Earth 33 (1–2), 28–40.

Hashimoto, T., Stedinger, J.R., Loucks, D.P., 1982. Reliability, resiliency and vulnerability criteria for water resource system performance evaluation. Water Resour. Res. 18 (1), 14–20.

Hassanzadeh, E., Zarghami, M., Hassanzadeh, Y., 2012. Determining the main factors in declining the Urmia Lake level by using system dynamics modeling. Water Resour. Manage. 26 (1), 129–145.

Hjorh, P., Bagheri, A., 2006. Navigation towards sustainable development: a system dynamics approach. Future 38 (1), 74–92.

Hutchinson, C.F., Varady, R.G., Drake, S., 2010. Old and new: changing paradigms in arid lands water management. In: Schneier-Madanes, G., Courel, M.F. (Eds.), Water and Sustainability in Arid Regions, vol. 3. Springer, pp. 311–332.

ICID, 2005. Experiences in inter-basin water transfers for irrigation, drainage or flood management (3rd draft 15 August 2005). Unpublished report. International Commission on Irrigation and Drainage ICID-CIID, New Delhi.

Israel, M., Lund, J.R., 1995. Recent California water transfer: implications for water management. Natur. Resour. J. 35, 1–32.

Jenkins, M.W., Lund, J.R., Howitt, R.E., Draper, A.J., Msangi, S.M., Tanaka, S.K., Ritzema, R.S., Marques, G.F., 2004. Optimization of California's water system: results and insights. J. Water Resour. Plann. Manage., ASCE 130 (4), 271–280.

Kittinger, J.N., Coontz, K.M., Yuan, Z.P., Han, D.J., Zhao, X.F., Wilcox, B.A., 2009. Toward holistic evaluation and assessment: linking ecosystems and human well-being for the Three Gorges Dam. EcoHealth 6 (4), 601–613.

Klaphake, A., 2005. Economic and political benefits of transboundary water cooperation. In: IHP-HWRP, the Value of Water – Different Approaches in Transboundary Water Management. Proceedings of the International Workshop, Koblenz, pp. 91–99.

Klein, C., 2007. Water transfers: the case against transbasin diversions in the Eastern States. UCLA J. Environ Law Policy 25 (2), 249–280.

Klemes, V., Srikanthan, R., McMahon, T.A., 1981. Long-memory flow models in reservoir analysis: what is their practical value? Water Resour. Res. 17 (3), 737–751.

Langsdale, S., Beall, A., Carmichael, J., Cohen, S., Forster, C., 2007. An exploration of water resources futures under climate change using system dynamics modeling. Integr. Assess. 7 (1), 51–79.

Langsdale, S., Beall, A., Carmichael, J., Cohen, S., Forster, C., Neale, T., 2009. Exploring the implications of climate change on water resources through participatory modeling: case study of the Okanagan Basin, British Columbia. J. Water Resour. Plann. Manage. 135 (5), 373–381.

Leal Neto, A.C., Legey, L.F.L., Gonzalez-Araya, M.C., Jablonski, S., 2006. A system dynamics model for the environmental management of the Sepetiba Bay watershed, Brazil. Environ. Manage. 38 (5), 879–888.

Lund, J.R., Hanak, E., Fleenor, W.E., Bennett, W.A., Howitt, R.E., Mount, J.F., Moyle, P.B., 2010. Comparing futures for the Sacramento–San Joaquin Delta. University of California Press, Berkeley, CA.

Madani, K., 2005. Watershed management and sustainability-A system dynamics approach (case study: Zayandeh-Rud River Basin, Iran). Thesis (Master). Lund University, Sweden.
Madani, K., 2007. A system dynamics approach to integrated watershed management. Hydrol. Sci. Technol. 23 (1–4), 147–158.
Madani, K., 2008. Reasons behind failure of qanats in the 20th century. In: Babcock, R.W., Walton, R. (Eds.), Proceeding of the 2008 World Environmental and Water Resources Congress. ASCE, Hawaii.
Madani, K., 2010. Towards Sustainable Watershed Management: Using System Dynamics for Integrated Water Resources Planning. VDM Verlag Dr. Müller, Saarbrücken, Germany, ISBN 978-3-639-18118-0.
Madani, K., in press. Modeling international climate change negotiations more responsibly: can highly simplified game theory models provide reliable policy insights? Ecol. Econ., doi: 10.1016/j.ecolecon.2013.02.011.
Madani, K., Lund, J.R., 2012. California's Sacramento–San Joaquin Delta conflict: from cooperation to chicken. Water Resour Plan Manage., ASCE 138 (2), 90–99.
Madani, K., Mariño, M.A., 2009. System dynamics analysis for managing Iran's Zayandeh-Rud river basin. Water Resour. Manage. 23, 2163–2187.
Maneta, M.P., Mo, T., Wallender, W.W., Vosti, S., Howitt, R., Rodrigues, L., Bossi, L.H., Pandy, S., 2009. A spatially distributed hydroeconomic model to assess the effects of drought on land use, farm profits, and agricultural development. Water Resour. Res. 45, W11412.
Mansoori, J., 1997. Ramsar Report for Gavkhouni Lake and Marshes of the Lower Zaindeh-Rud. The Ramsar Sites Database.
Matete, M., Hassan, R., 2006. Integrated ecological economics accounting approach to evaluation of inter-basin water transfers: an application to the lesotho highlands water project. Ecol. Econ. 60 (1), 246–259.
McMahon, T.A., Adeloye, A.J., Sen-Lin, Z., 2006. Understanding performance measures of reservoirs. J. Hydrol. 324 (1–4), 359–382.
Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W., 1972. The Limits to Growth. Universe Book, New York, p. 205.
Medellin-Azuara, J., Harou, J.J., Olivares, M.A., 2008. Adaptability and adaptation of California's water supply system to dry climate warming. Clim. Change 87 (Suppl. 1), S75–S90.
Medellin-Azuara, J., Mirchi, A., Madani, K., 2011. Water supply for agricultural, environmental and urban uses in California's borderlands. In: Contreras, L.M. (Ed.), Agricultural Policies: New Developments. Nova Science Publishers, New York, pp. 201–212.
Mirchi, A., Watkins, D., in press. A systems approach to holistic TMDL policy: the case of Lake Allegan, Michigan. J. Water Resour. Plann. Manage., ASCE, doi:10.1061/(ASCE)WR.1943-5452.0000292.
Mirchi, A., Watkins, D., Madani, K., 2010. Modeling for watershed planning, management, and decision making. In: Vaughn, J.C. (Ed.), Watersheds: Management, Restoration and Environmental Impact. Nova Science Publishers, New York.
Mirchi, A., Madani, K., Watkins, D., Ahmad, S., 2012. Synthesis of system dynamics tools for holistic conceptualization of water resources problems. Water Resour. Manage. 26 (9), 2421–2442.
Morid, S., 2003. Adaptation to climate change to enhance food security and environmental quality: Zayandeh Rud Basin. Iran. ADAPT Project Final Report. Tarbiat Modares University, Tehran, p. 50.
Motiee, H., McBean, E., Semsar, A., Gharabaghi, B., Ghomashchi, V., 2006. Assessment of the contributions of traditional qanats in sustainable water resources management. Water Resour. Develop. 22 (4), 575–588.
Muller, M., 1999. Interbasin water sharing: a South African perspective. In: Proceedings of the International Workshop on Interbasin Water Transfer, 25–27 April 1999. UNESCO, Paris, pp. 61–70.
Nikouei, A., Zibaei, M., Ward, F.A., 2012. Incentives to adopt irrigation water saving measures for wetlands preservation: an integrated basin scale analysis. J. Hydrol. 464–465, 216–232.
Olden, J.D., Naiman, R.J., 2010. Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. Freshwater Biol. 55 (1), 86–107.
Iran Ministry of Energy's Office for Water and Wastewater Macro-Planning (OWWMP), 2010. Iran's comprehensive water resources plan using an integrated water resources management approach in Eastern Basins: Potentials and status assessment of water resources development. Groundwater Resources Report, UCP/HGY-42-01 (in Persian).
Qaiser, K., Ahmad, S., Johnson, W., Batista, J., 2011. Evaluating the impact of water conservation on fate of outdoor water use: a study in an arid region. J. Environ. Manage. 92 (8), 2061–2068.
Richmond, B., 1993. Systems thinking: critical thinking skills for the 1990s and beyond. Syst. Dyn. Rev. 9 (2), 113–133.
Sandoval-Solis, S., McKinney, D.C., Loucks, D.P., 2011. Sustainability index for water resources planning and management. J. Water Resour. Plann. Manage., ASCE 137 (5), 381–390.
Scheuerlein, H., 1999. Interbasin water transfer from the Danube to the Rhine Basin in Bavaria. In: Proceedings of the International Workshop on Interbasin Water Transfer, 25–27 April, 1999. UNESCO, Paris, pp. 107–114.
Schumann, H., 1999. Water transfer systems for fresh water supply in Germany. In: Proceedings of the International Workshop on Interbasin Water Transfer, 25–27 April, 1999. UNESCO, Paris, pp. 115–122.
Soil Conservation Service (SCS), 1972. Hydrology. In: National Engineering Handbook, Section 4. GPO, Washington, DC.
Sehlke, G., Jacobson, J., 2005. System dynamics modeling of transboundary systems: the Bear River Basin model. Ground Water 43 (5), 722–730.
Senge, P.M., 1992. The Fifth Discipline: The Art & Practice of the Learning Organization. Doubleday Currency Press, New York.
Shahbazbegian, M., Bagheri, A., 2010. Rethinking assessment of drought impacts: a systemic approach towards sustainability. Sustain. Sci. 5 (2), 223–236.
Shao, X., Wang, H., Wang, Z., 2003. Interbasin transfer projects and their implications: a China case study. Int. J. River Basin Manage. 1 (1), 5–14.
Simonovic, S.P., 2009. Managing water resources, methods and tools for a system approach. United Nations Educational, Scientific and Cultural Organization. UNESCO Publishing, Paris, p. 640.
Simonovic, S.P., Ahmad, S., 2005. Computer-based model for flood evacuation emergency planning. Nat. Hazard 34 (1), 25–51.
Simonovic, S.P., Fahmy, H., 1999. A new modeling approach for water resources policy analysis. Water Resour. Res. 35 (1), 295–304.
Simonovic, S.P., Li, L., 2003. Methodology for assessment of climate change impacts on large-scale flood protection system. J. Water Resour. Plann. Manage. 129 (5), 361–371.
Simonovic, S.P., Rajasekaram, V., 2004. Integrated analyses of Canada's water resources: a system dynamics approach. Can. Water Resour. J. 29 (4), 223–250.
Soltani, S., 2009. Determining the Minimum Water Requirements (Water Right) of Gavkhoni Wetland. A cooportive work of Isfahan University of Technology and Isfahan Environmental Organization, Iran.
Stave, K.A., 2003. A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. Environ. Manage. 67 (4), 303–313.
Sterman, J.D., 2000. Business Dynamics, Systems Thinking and Modeling for A Complex World. McGraw-Hill, Boston.
Stewart, S., Valdés, J., Gastélum, J., Brookshire, D., Aparicio, J., Hidalgo, J., Velazco, I., 2004. A decision support system for demand management in the Rio Conchos Basin, México. In: Proceedings of Hydrology: Science and Practice for the 21st Century. British Hydrological Society, vol. II, pp. 487–494.
Tanaka, S.K., Connell-Buck, C.R., Madani, K., Medellin-Azuara, J., Lund, J.R., Hanak, E., 2011. Economic costs and adaptations for alternative regulations of California's Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science, vol. 9(2). <http://www.escholarship.org/uc/item/3z016702>.
Tangirala, A.K., Teegavarapu, R.S.V., Ormsbee, L., 2003. Modeling adaptive water quality management strategies using system dynamics simulation. Environ. Inf. Arch. 1, 245–253.
Tidwell, V.C., Passell, H.D., Conrad, S.H., Thomas, R.P., 2004. System dynamics modeling for community-based water planning: application to the Middle Rio Grande. Aquat. Sci. 66, 357–372.
UN-Water, 2005. A Gender Perspective on Water Resources and Sanitation. Interagency task force on gender and water. In: The 12th Session of the Commission on Sustainable Development.
UN-Water, 2008. Status report on integrated water resources management and water efficiency plans. In: The 16th Session of the Commission on Sustainable Development.
Vakil, H.A., 2006. Gavkhooni Swamp to Turn into an International Tourism Destination. Skyscrapercity: Tourism Infrastructure, Development and News.
Varady, R., 1999. Inter basin water transfers: in the south-western United States: the case of the San Pedro River. In: Proceedings of the International Workshop on Interbasin Water Transfer, 25–27 April, 1999. UNESCO, Paris, pp. 71–73.
Venkatesan, A.K., Ahmad, S., Johnson, W., Batista, J.R., 2011. System dynamics model to forecast salinity load to the Colorado River due to urbanization within the Las Vegas Valley. Sci. Total Environ. 409 (13), 2616–2625.
Vezjak, M., Savsek, T., Stuhler, E.A., 1998. System dynamics of eutrophication processes in lakes. Eur. J. Oper. Res. 109 (2), 442–445.
Winz, I., Brierly, G., Trowsdale, S., 2009. The use of system dynamics simulation in water resources management. Water Resour. Manage. 23 (7), 1301–1323.
Wolstenholme, E.F., 2003. Towards the definition and use of a core set of archetypal structures in system dynamics. Syst. Dyn. Rev. 19 (1), 7–26.
Wright, G., 1999. Interbasin water transfers: the Australian experience with the snowy mountains scheme. In: Proceedings of the International Workshop on Interbasin Water Transfer, 25–27 April, 1999. UNESCO, Paris, pp. 101–105.
Wulff, H.E., 1968. The qanats of Iran. Sci. Am. 218 (4), 94–105.
Xu, Z.X., Takeuchi, K., Ishidaira, H., Qhang, X.W., 2002. Sustainability analysis for Yellow River water resources using the system dynamics approach. Water Resour. Manage. 16 (3), 239–261.
Yan, D.H., Wang, H., Li, H.H., Wang, G., Qin, T.L., Wang, D.Y., Wang, L.H., 2012. Quantitative analysis on the environmental impact of large-scale water transfer project on water resource area in a changing environment. Hydrol. Earth Syst. Sci. 16, 2685–2702.
Zayandab Consulting Engineering Co., 2008. Determination of resources and consumptions of water in the Zayandeh-Rud River Basin. Iran.
Zhu, T., Lund, J.R., Jenkins, M.W., Marques, G.F., Ritzema, R.S., 2007. Climate change, urbanization, and optimal long-term floodplain protection. Water Resour. Res. 43, W06421.