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System Dynamics Analysis for Managing Iran's Zayandeh-Rud River Basin

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Abstract Within river basins different social, economic, political and physical subsystems interact. When making decisions, policy makers should be aware of such interactions as any new policy will affect more than one subsystem. To determine the adequacy of a specific management policy, an integrated study is needed of a complicated water management system in the basin considering major physical, social, economic and political aspects. The Zayandeh-Rud river basin, in central Iran with a semi-arid climate and large agricultural, industrial and domestic water uses, is an example of a complicated watershed system where the lack of complete knowledge about all the interacting subsystems has led to failure of the policy makers in addressing the water shortage in the basin. Although water shortages occur fairly soon after completion of each new water source, transbasin water diversion is still the major policy of water planners to address ongoing shortages. System dynamics provides a unique framework for integrating the disparate physical, socio-economic and political systems important to watershed management. This approach is used to comprehend the interactions of different drivers of the problem and to convey the experiences, lessons learned, and perceptions gained during the model development process. A simulation model, built based on causal loop diagrams of the problem, shows that transbasin diversion is not the best and only solution to the problem. The results of the model for different scenarios suggest that various options of demand management and population control can be more effective in addressing the water crisis of the basin when combined with transbasin water diversions, increasing water storage capacity and controlling of groundwater withdrawal.

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1 Introduction

High agricultural water use and growing human population and industry, together with droughts in the Zayandeh-Rud river basin have made water resource management a critical issue in the region. To address this challenge, water managers in the basin have completed several water transfer projects and retained additional water transfer as their main policy to respond to increasing water demand. While Morid et al. (2003) suggested water transfer from neighboring basins as an essential adaptation action in case of climate change in coming years, Murray-Rust et al. (2002) concluded that shortages occur almost rapidly after each new water transfer as it raises the residents' expectations and increases water demand and perhaps water diversion is not a sustainable solution to the problem.

Study of the Zayandeh-Rud watershed provides an example of how water managers in a water-short basin have tried to match supply and demand over the past decades without enough knowledge about the effects of their policies on other aspects of the complicated watershed system. To date, the growing demand of the basin has largely been met by interbasin water transfer, and by mining fossil groundwater resources. However, both solutions have some physical limits. Bringing future demand in line with available supplies will require increasingly efficient water management practices and greater conservation of water (Tidewell et al. 2004). The basin has experienced the technical and socio-political outcomes of different interbasin water transfers, which are really important from an engineering and managerial point of view and can be quite instructive for the planners of such kind of projects.

Management of water basins benefits from the development and application of diverse models that offer a comprehensive and integrated view of these complex systems and the demands placed upon them (Tidewell et al. 2004). The power of developed dynamic regional models can increase our understanding of water problems and the ability to explore sustainable solutions (Simonovic 2002). To determine if water import is the best solution to avoid water shortages in the basin, an integrated study is needed of a complicated water management system in the basin considering major physical, social, economical and political aspects of it. Here, the Zayande-Rud Watershed Management and Sustainability Model (ZRW-MSM) is developed within a system dynamics framework (Forrester 1961, 1968; Sterman 2000) to comprehend the dynamic and interrelated characteristics of the system; and convey experiences, lessons learned, and perceptions gained through the model development process.

In the following sections of the paper, after describing the study area and water management problem, the system dynamics method used for solving the problem is introduced. Then the problem's modeling process starts with the development of a conceptual model based on causal loop diagrams (CLDs) of the problem which will be the basis for quantifying the model and developing the quantitative model (ZRW-MSM). Future scenarios are defined and the model is run for each scenario to investigate the behavior patterns of the management variables of interest. The paper ends with a discussion of the benefits of applying system dynamics for solving water resource management problems and some conclusions and recommendations specific to water management of the study area.

2 Overview of the Study Area

Table 1 presents a brief overview of the study area (Fig. 1). The Zayandeh-Rud river is the highest-volume river in semi-arid central Iran and forms one of the most strategic and important river basins of Iran with large agricultural, industrial, and domestic water uses. The Zayandeh-Rud river starts in the Zagros Mountains in the southwest of the country and ends in the Gav-Khuni Swamp, a natural salt pan in the center of Iran. On its long journey, the Zayandeh-Rud river is tapped by an increasing number of agricultural, urban, and industrial users. Only a trickle of water flows into the Gav-Khuni Swamp where the river ends in eastern Iran. As a result, the wetland area of Gav-Khuni, recognized internationally under the Convention on Wetlands (1971), no longer receives an adequate quantity of water.

According to the national census of 1996, more than 3.1 million residents were living in the Zayandeh-Rud river basin. Currently, the mean annual population growth rate is estimated to be 2.14%. The high population growth rate is mostly from immigration from neighboring regions. Desirable job opportunities due to industrial development and availability of land and water (compared to neighboring regions), motivates immigrants to move to this basin which leads to more water demand. Water demand is rising annually not merely through population growth but also because more affluent people consume more water per capita. Similar to the rest of the country, population distribution in the Zayandeh-Rud river basin is very uneven because of the enormous variations in natural and climatic conditions, availability of water and land, economic potentials, and concentration of industries and services across the watershed. The population compression index in the Zayandeh-Rud river

Table 1 Overview of the study area

Metric	Value
Total area of the basin (km^2)	41,524
Elevation range (m a.s.l)	1,470–3,974
Annual average precipitation range (mm)	50–1,500
Average temperature range (°C)	3–30
Annual potential evapotranspiration (mm)	1,500
Zayandeh-Rud river length (km)	350
Natural average flow of Zayandeh-Rud river (mcm)	850
Gav-Khuni marsh minimum required input flow (mm)	70
Population in 1996 (capita)	3,104,000
Mean annual population growth rate in 1996 (%)	2.14
Total area under irrigation (ha)	260,000
Irrigation efficiency range (%)	35–39
Annual economic development rate of the basin (%)	4.2
Share of agricultural section from the total consumed water (%)	90
Share of industrial section from the total consumed water (%)	5
Share of domestic section from the total consumed water (%)	5

Fig. 1 Topographic map of Zayandeh-Rud (Gav-Khuni) Water Basin (Salemi et al. 2000)

basin is more than twice as it is in the rest of the country (Jamab Consulting Engineering Co 1998).

Agriculture is the largest single water user in the basin despite increased demands from other users. Because of low precipitation in the central and eastern portions of the basin, irrigation is essential to the cultivation of crops (wheat, barely, silage plants, potatoes, cotton, paddy orchards, etc.) on about 260,000 ha of irrigated land. Similar to other parts of Iran, the rainy season does not coincide with the cultivation season in this basin and during summer there is no effective rainfall. Low irrigation efficiency, approximately 35–39%, exacerbates the situation (Jamab Consulting Engineering Co 1998). About 90% of water in Zayandeh-Rud basin is consumed for agriculture while only about 7% of the watershed area is used for agriculture (Jamab Consulting Engineering Co 1998). Although there are substantial return flows to the Zayandeh-Rud river, they are of lower quality than the diverted water and may not be suitable for downstream users. Share of the domestic sector from the total consumed water in the basin is approximately 5%. Most of this share is wasted due to network leakages and the real domestic consumption of the residents is below this amount. The most likely annual economical development rate for the Zayandeh-Rud river basin has been estimated to be 4.2% (Jamab Consulting Engineering Co 1998).

Water resource development in the Zayandeh-Rud river basin has had several stages in the course of history. Table 2 presents a brief description of six development phases of water supply in Zayandeh-Rud river basin. Until 1952 water resources development were confined primarily to small diversion structures that provided irrigation water to riverine irrigation systems in the central part of the valley. Irrigation was primarily confined to the springs, qanats and early summer when snowmelt provided sufficient discharge, but was of minimal importance in full summer and autumn. In response to increasing water demand, water transfer projects started after World War II and are going to be continued. These water imports have more than

Table 2 Water supply development phases in the Zayandeh-Rud river basin

Phase	Description	Annual capacity (mcm)[a]	Estimated annual yield (mcm)[b]
I—Before 1952	Exploitation of Zayandeh-Rud river	NA	850
II—1952	Construction of Kuhrang transbain diversion tunnel No. 1	337	297
III—1972	Construction of Zayandeh-Rud (Chadegan) Dam	1,500	NA
IV—1985	Construction of Kuhrang transbain diversion tunnel No. 2	250	246
V—2004	Construction of Cheshmeh-Langan transbasin diversion tunnel	150	120
VI—2007	Construction of Kuhrang transbain diversion Tunnel No. 3	280	268

[a] Murray-Rust et al. (2002)

[b] Isfahan and Chaharmahal-va-Bakhtiari Water Authority (2003)

doubled the natural flow of the Zayandeh-Rud river. The political and economic power of Isfahan Province, covering most of the area of this basin, has resulted in a large amount of water transfers to the basin while the neighboring basins still suffer from water shortage, unable to import water.

Since 2002, outgoing transbasin water diversion projects started to take only 34 mcm from the Zayandeh-Rud river to cities in the central desert of Iran. Nonetheless, this water amount is reasonably critical for the neighboring under pressure water basins. Thus, right now, the Zayandeh-Rud river basin is more important than before because of the high reliance of the neighboring water basins on the water conditions in this basin. The outgoing transferred flow will increase up to 152 mcm until 2011 and other cities in neighboring watersheds will also consume Zayandeh-Rud river's water (Isfahan and Chaharmahal-va-Bakhtiari Water Authority 2003). A detailed description of the Zayandeh-Rud river basin is contained in Najafzadeh (2004) and Madani Larijani (2005).

3 Problem Description

The river currently provides water for over 3 million people in the Zayandeh-Rud river basin and over another 1.5 million people in small and large cities hundreds of kilometers outside the river basin. In addition, the river provides irrigation water for over 260,000 ha of farmland and tries to meet the demands of the second largest industrial area of Iran. The Gav-Khuni marshland receives something less than half of the amount of water which is necessary to sustain the wetland habitat for fauna and flora (Salemi et al. 2000). Today, the available water per capita in this basin is about 1,150 m^3 per year, which is relatively a poor volume compared to some other Iranian basins. Water management in the river basin is currently challenged with providing sufficient water supply for various user groups in the face of increasing demands.

The main problem, which is common to other arid/semi-arid environments in the country, is to balance a highly variable water supply among the demands posed by growing population, irrigated agriculture, and industrial development. The increasing demand has led to competition of the domestic and industrial sectors with the agricultural sector, resulting in significant gaps between actual and potential yields and a reduction in return flows into the Zayandeh-Rud river (ISOE 2006). Water use by domestic, industrial, agricultural and environmental users has exceeded available surface supply and caused decreasing groundwater tables. If unrestricted groundwater use is continued, available groundwater will most likely be exhausted. The semi-arid climate of the basin and droughts result in hindrances of water planning, making the situation harder for the water policy makers who intend to supply the region with sustainable water resources. The Zayandeh-Rud river does not supply enough water to the Gav-Khuni marshland, which is world-class natural wetland and is threatened with environmental destruction.

Since water managers of the basin assume that all the user groups will always increase their demands for water, their main policy is bringing more water to the basin. Some of shortfalls in water are met through transbasin diversions, however, this will not automatically reverse the trends towards less water consumption (Murray-Rust et al. 2002). Over the second half of the twentieth century, a series of water resource development projects have doubled the potentially available water in the basin. Nevertheless, water shortages have occurred fairly rapidly after each new water source has been tapped. As soon as more water is made available, it is fully allocated so that there is no reserved water resource for use in droughts. Thus, when winter precipitation falls below average, the water supply in the following summer is highly vulnerable (Murray-Rust et al. 2002). Murray-Rust et al. (2002) concluded that responses to shortfalls in supply appear to be ad-hoc and uncoordinated. Only the awareness that providing more water capacity is creating more demands on water, by encouraging more use by agricultural and industrial interests, led Iranian water managers to radically rethink their water policy.

To better respond to the problem, water resource managers need to know more about the interactions of different drivers of the problem. Armed with that knowledge, they can find out if the transbasin water diversion will be adequate to address the crisis or whether other measures will be required for providing a sustainable water supply.

4 Method

A model is needed which provides an integrated view of the watershed, one that couples the complex physics governing water supply with diverse socio-economical, political, and environmental issues driving water demand. This model should be dynamic in nature and explicitly capture the dynamic feedbacks between physical characteristics of water balance and population growth, development of agriculture and industry, economic development, and use of other resources. Thus, an approach will be adopted based on the principles of system dynamics (Forrester 1961, 1968; Sterman 2000). System dynamics modeling and simulation is specifically designed for modeling and analysis of large-scale socio-economic systems and has been applied in many environmental and water resource studies, including water resource planning and management (Ford 1996; Simonovic 2002; Zu et al. 2002; Stave 2003; Simonovic and Li 2004; Tidewell et al. 2004; Ahmad and Simonovic 2006; Bagheri 2006; Croke et al. 2007; Feng and Huang 2008; Yang et al. 2008), and environmental sustainability (Forrester 1971; Meadows et al. 1992; Saysel et al. 2002). System dynamics which provides a unique framework for integrating the disparate physical and social systems important to water resource management is formulated on the premise that the structure of a system, the network of cause and effect relations between system elements, governs the overall system's behavior (Sterman 2000).

The systems approach is a discipline for seeing the structures that underlie complex domains. System dynamics is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshots, and for seeing processes rather than objects (Simonovic and Fahmy 1999). The major concept of the system dynamics simulation approach is feedback which is used as the basis for structuring description of complex systems and their economic, social, political, and environmental implications (Bender and Simonovic 1996).

The typical purpose of a system dynamics study is to realize how and why the dynamics of concern are generated and to look for managerial policies that can improve the situation (Saysel et al. 2002). In system dynamics studies, the problem is often decomposed into a temporally dynamic, spatially aggregated system. Systems are modeled as networks of stocks and flows with feedback relationships between the various stocks and flows comprising each system. Feedbacks are not always realized instantaneously but may be delayed in time (Tidewell et al. 2004). This methodology focuses on understanding how the physical processes, information flows and managerial policies interact so as to create the dynamics of the different variables of interest. The totality of the relationships between the system's components constitutes the system's structure, which over time may generate some type of dynamic behavior such as exponential growth or decline.

Every decision is made within a feedback loop which is a closed loop of causes and effects. Basically, there are two different types of dynamic feedback archetypes: (1) reinforcing (positive) loop and (2) balancing (negative) loop.

Reinforcing loops are the engines of growth and cause the system to gain momentum in time, either growing or declining. Examples of these would be a savings account where interest continuously accrues at an increasing rate on the principal or a cancer which metastasizes exponentially if therapeutic interventions are not taken. Nonetheless, pure accelerating growth or decline rarely continues unchecked in nature, since reinforcing processes hardly ever occur in isolation. Usually, limits are encountered eventually somehow to slow down the process (Bender and Simonovic 1996).

Balancing feedbacks, which operate whenever there is a target-oriented behavior, drive the system to transform toward an external goal. If the system is moved from its goal by some change, the negative feedback tries to balance the system by neutralizing the effects of that move. For instance, a cancer patient undergoes chemotherapy to return to a normal healthy state. Since in public decision making the goals are often implicit, no one recognizes that the balancing process exists at all. This makes the balancing process difficult and balancing loops are, in general, more difficult to see than reinforcing loops (Bender and Simonovic 1996).

In this study, based on system dynamics principles, a causal loop diagram (CLD) is developed for the Zayandeh-Rud watershed problem, considering the hydrological, environmental, economical, political and social drivers of the problem and their interactions. This CLD is used to construct a simulation model (ZRW-MSM) which will be run for different future scenarios to examine the dynamic interaction of different parameters of the system and to explore the behavior patterns of variables of interest.

5 Modeling

In this study, the modeling process has two main stages. The first stage is development of a conceptual model or a Casual Loop Diagram (CLD) of the problem in which the elements of the model and the causal relationships among them were identified. Based on the CLD of the problem, it should be possible to guess or estimate the behavior of different variables of interest and the overall behavior pattern of the system. The second stage is development of a simulation model or the Stock Flow Diagram of the problem based on the conceptual model and the actual recorded data in the region. At this stage, it is possible to observe the behavior patterns of different parameters in terms of graphs and numbers to validate the CLD of the problem and build trust in the model. In system dynamics studies the emphasis in on understanding trends and behaviors rather than values and numbers.

5.1 Conceptual Model

Two subsystems are identified for the Zayandeh-Rud water resources management system, a “Hydrologic Subsystem” and a “Socio-Political and Economic Subsystem”. Since the system dynamics method deals with a system using an integrated approach, clarification of individual subsystems is essential for this integration. This allows interactive relationships among the subsystems to be clarified, and the embedded links among system components to be identified. In large systems, changes in one subsystem may lead to effects on and responses from the other components of the system which should not be neglected in integrated studies of the system. Here, a CLD is developed for each of the subsystems. The combination of the two CLDs would be the CLD of the whole problem.

5.1.1 Hydrologic Subsystem

Figure 2 shows the developed CLD of the problem for the Hydrologic Subsystem. On the diagrams each arrow represents a cause and effect relationship. The polarity of the link (+/-) indicates the direction of change induced by a cause. A positive sign indicates change in the same direction (increase/decrease induces increase/decrease) while a negative sign indicates change in the reverse direction (increase/decrease induces decrease/increase). For instance, based on Fig. 2, as available surface water increases, percolation to groundwater will increase. There is a negative feedback relationship between these two variables as well, meaning that an increase in percolation results in a decrease in available surface water. The combination of positive and negative relations between these two variables forms a balancing loop together. Here, the negative feedback tries to minimize the effects of the change in the state of the system (the amount of available surface water).

5.1.2 Socio-Political and Economical Subsystem

Figure 3 shows the CLD of the problem for the Socio-Political and Economic Subsystem. It is assumed that per capita water consumption and economic development rate

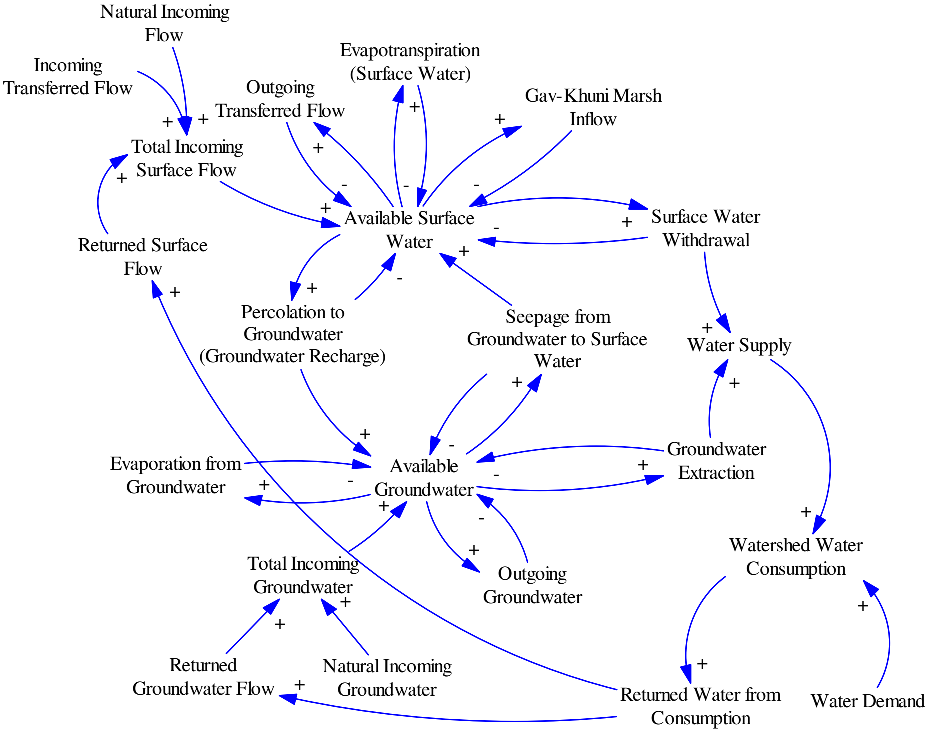


Fig. 2 CLD of the problem for the hydrologic subsystem

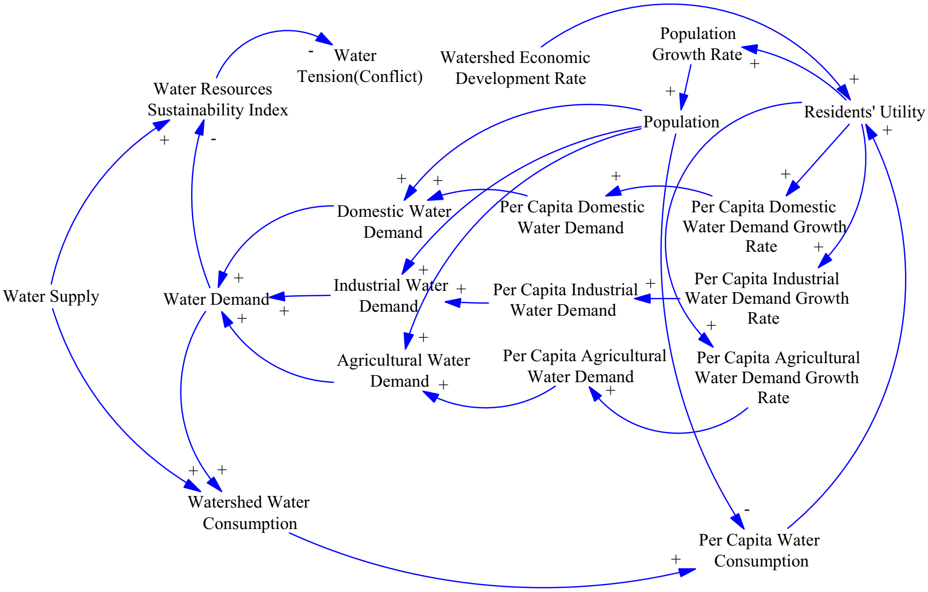


Fig. 3 CLD of the problem for the socio-political and economic subsystem

of the region, together, determine the utility of the residents (utility is an economic term which refers to the total satisfaction of a resident from a good or service. Here, residents' utility refers to the total satisfaction of the watershed's residents from the available services in the water basin). Residents' utility has positive relations with population growth rate and different water demand growth rates. Consequently, if residents' utility rises/falls such growth rates will increase/decrease. With an increase/decrease in water demand growth rates, population of the basin and per capita water demand in each sector increases/decreases, respectively. Per capita water demand of each sector together with population determines water demand of each sector. Water demand of the watershed is considered to be the sum of water demand of each sector. Both water demand and water supply have positive relations with water consumption of the region. Population has a negative relation with per capita water consumption. By an increase/decrease in population, the share of each resident from the amount of consumed water will decrease/increase to decrease/increase per capita water consumption. One variable that could be included in the CLD but is absent in Fig. 3 is water price. Water price has a negative relation with residents' utility and an increase in water price can decrease the residents' utility and consequently the total water demand if residents' utility is price elastic. In Iran, in general, and in the Zayandeh-Rud river basin in particular, the current water demand is almost inelastic to water price because government is the only provider of highly subsidized cheap water. Agricultural water use, which amounts to about 90% of the total consumed water, is very cheap and the government cannot easily raise the price due to political obstacles. Previous increases in agricultural water price have resulted in farmers' strikes.

Figure 4 is an abbreviation of Fig. 3 showing on the main loops of the socio-political and economic subsystem. In this figure, B represents a balancing loop while R stands for a reinforcing loop. The whole system is composed of two reinforcing (positive) loops and one balancing (negative) loop. Thus, this CLD has a negative polarity overall.

If only the two reinforcing loops of Fig. 4 are considered, without interference of the balancing loop, residents' utility, population, per capita water demand, watershed's water demand, water consumption and per capita water consumption grow or decline one after another as a result of rise or fall in the value of any of them. For instance, if the residents' utility rises all other variables increase continuously. The feedback relationship raises the residents' utility which in turn continuously increases the value of all the variables of the CLD except the water supply and economic development rate. If this behavior continues, the overall system moves unsustainably. However, the balancing loop interferes and changes the situation. An increase in population induces a decrease in per capita water consumption, which lowers residents' utility. In natural systems, balancing loops always seek neutralization of the effects of reinforcing loops, which bring an unsustainable behavior to the system and reinforcing loops rarely remain unchecked. However, in search of benefits, humans have changed the sustainable behavior of many natural systems by weakening the functionality of natural-balancing systems in favor of humans without considering the disastrous effects of such actions on those natural systems. After a long period of unbalancing natural systems for various purposes, in today's world various environmental groups are struggling to bring back the original behavior of these systems by eliminating or minimizing the effects of human

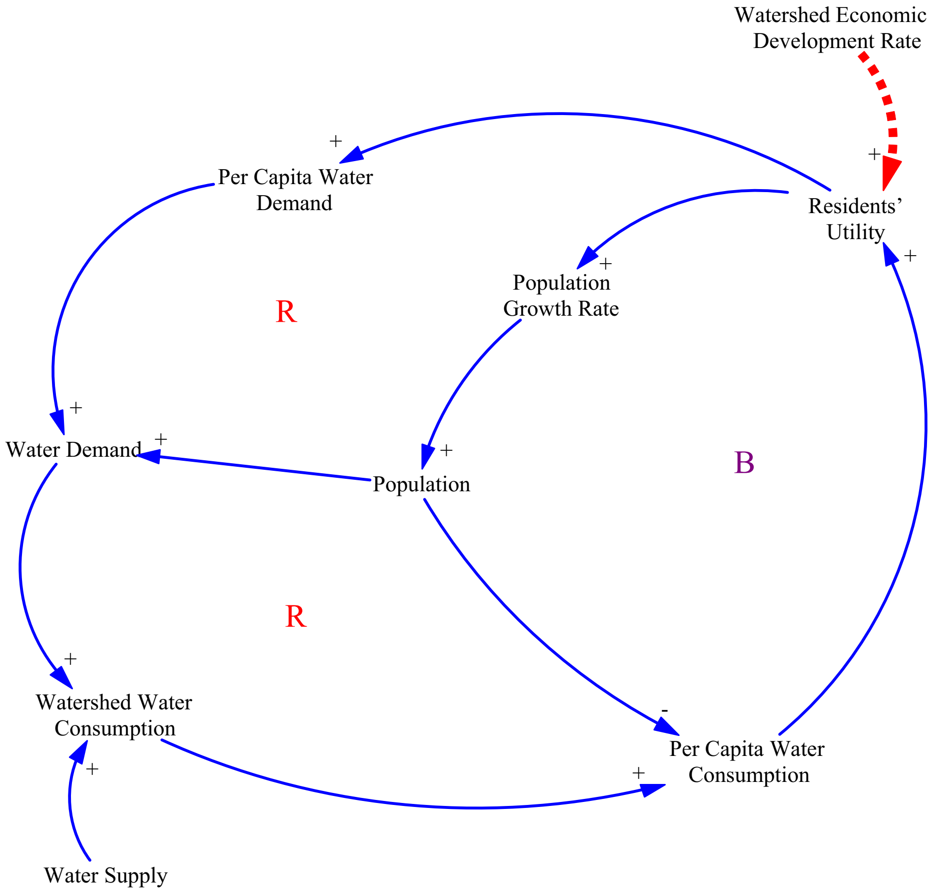


Fig. 4 Main loops of socio-political and economic subsystem

activities on the system and strengthening the functionality of natural balancing loops.

Here, based on the CLD, it is observed that residents' utility is not a function of per capita water consumption only. The economic development rate of the region has a positive relation with residents' utility. This parameter changes the natural behavior of the system and neutralizes the negative impact of the per capita water consumption variable. In other words, the impact of the balancing loop will fade away to some extent. The economic development of the region which is followed by good job opportunities and good living standards raises the utility of the residents. This motivates more people to immigrate to the water basin with good economic conditions, neglecting the availability of water.

The CLD for the Zayandeh-Rud river basin problem is the combination of hydrological and socio-political and economic subsystems' CLDs. Water supply, water demand and watershed water consumption are the elements of the boundary layer of each subsystem, connecting the subsystems to build up the overall CLD. This

CLD clarifies the interaction of different parameters and drivers of the Zayandeh-Rud watershed's problem and might be helpful in different management and decision making processes regarding water issues in the basin.

5.2 Stock and Flow Diagram

Based on the CLD of the problem it is possible to develop a Stock Flow Diagram of the problem to better characterize the system processes graphically, as the CLD of the problem fails to capture the stock and flow structure of systems. In the context of system dynamics, variables are either stocks or flows. Stocks are accumulations, such as the amount of water in a reservoir. Generally, stock variables characterize the state of the system and generate the information upon which decisions and actions are based. Flow variables represent rates which can change stock variables. For instance, the amount of water in a reservoir (a stock variable) is altered by inflows and outflows (flow variables). (Simonovic 2008).

5.2.1 Model Structure

Figures 5 and 6 indicate the Stock and Flow Diagrams of the hydrological subsystem and the socio-political and economic subsystem, respectively, which were developed based on Figs. 2 and 3. The Stock and Flow Diagram for the Zayandeh-Rud river

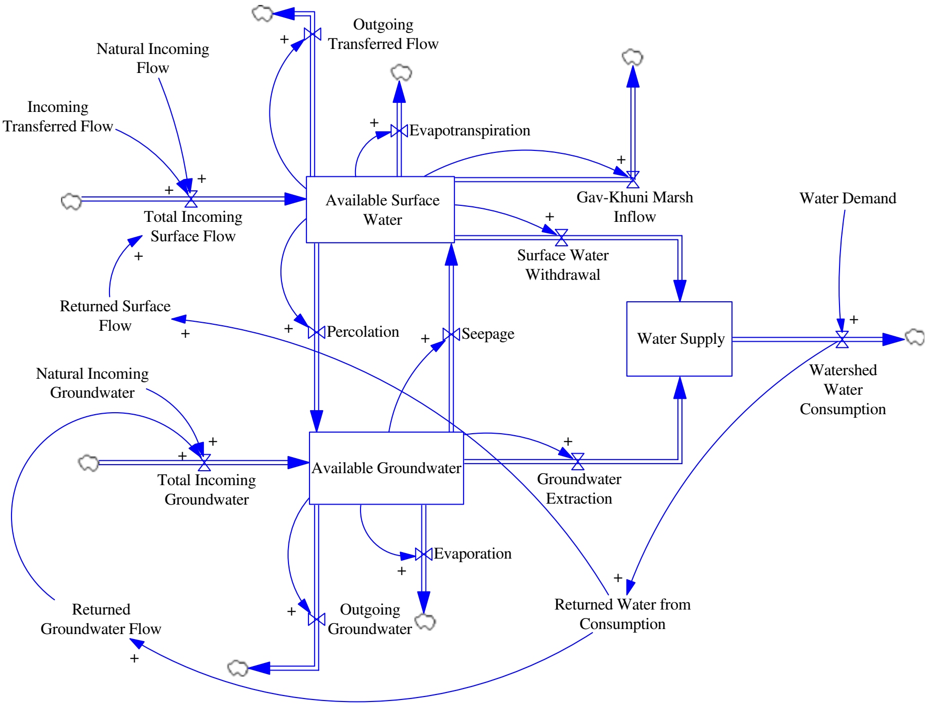


Fig. 5 Stock and flow diagram of the hydrologic subsystem

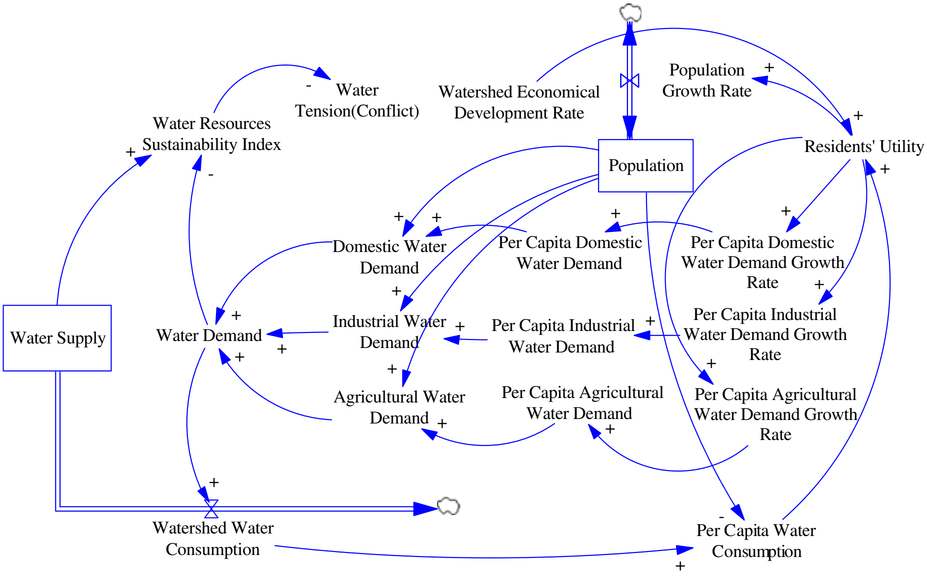


Fig. 6 Stock and flow diagram of the socio-political and economic subsystem

basin problem is the combination of hydrological and socio-political and economic subsystems' Stock and Flow Diagrams. Stock variables of the problem are the available surface water, available groundwater, water supply, and population. Stock variables increase by the inflows and decrease by the outflows. Available water is increased by the total incoming surface flow and groundwater seepage and decreased by evapotranspiration, percolation to groundwater, outgoing surface flow, surface water withdrawal, and the amount of inflow to the Gav-Khuni Marsh. Available groundwater is increased by the flow variables of total incoming groundwater and percolation from surface water and decreased by the flow variables of evaporation, seepage, and groundwater extraction. Similarly, the stock variable of water supply is increased by its inflows (surface water withdrawal and groundwater extraction) and decreased by its outflow (watershed water consumption). Population is controlled by the population growth rate. A positive population growth rate creates an inflow to the system which results in population increase while a negative rate results in an outflow and population decrease.

5.2.2 Model Equations

Based on the CLD of the hydrologic subsystem (Fig. 2), mass balances are developed in the model. For instance, the primary source of water in the basin is the upper catchment of the Zayandeh-Rud. Other perennial streams have little regional importance and do not reach into the main part of the basin. Thus, the total incoming surface flow (*TISF*) in the Zayandeh-Rud river basin is the sum of natural Zayandeh-Rud flow (*NF*), the amount of incoming transferred flow (*ITF*), and the returned surface flow (*RSF*) from consumption which continuously flows into the river as long as its 350 km journey to the Gav-Khuni marshland Eq. 1:

$$TISF = NF + ITF + RSF \tag{1}$$

Similarly, other equations can be developed based on the hydrologic CLD:

$$ASW = TISF + S - (E + P) \tag{2}$$

$$G - KI = ASW - (OTF + SWW) \tag{3}$$

$$TIGW = NIGW + RGWF \tag{4}$$

$$AGW = TIGW + P - (S + OGW + E_{GW}) \tag{5}$$

$$WS = SWW + GWE \tag{6}$$

where ASW = available surface water; *TISF* = total incoming surface flow; S = seepage; E = evapotranspiration; P = percolation to groundwater; $G\text{-}KI$ = Gav-Khuni marsh inflow; *SWW* = surface water withdrawal; *OTF* = outgoing transferred flow; AGW = available groundwater; *TIGW* = total incoming groundwater; *NIGW* = natural incoming groundwater; *RGWF* = returned groundwater flow; *OGW* = outgoing groundwater; *EGW* = evaporation from groundwater; *AGW* = available groundwater; *WS* = water supply; *SWW* = surface water withdrawal; and *GWE* = groundwater extraction.

Generally, stocks accumulate the difference between its inflow and outflow. Thus, a stock with a single outflow and single outflow can be mathematically formulated as:

$$Stock\,(t) = \int_{t_0}^{t_n} \left[Inflow\,(t) - Outflow\,(t)\right] dt + Stock\,(t_0) \tag{7}$$

where: *Stock*(t) = the amount of stock at time t, *Inflow*(t) = is the inflow at time t, and *Outflow*(t) = the outflow at time t, and t is any time between t_o and t_n ($t_o \leq t \leq t_n$).

Based on Fig. 5 and considering Eq. 7, Eqs. 1–6 can be rewritten as:

$$TISF\,(t) = \int_{t_0}^{t_n} \left[NF\,(t) + ITF\,(t) + NSF\,(t)\right] dt + TISF\,(t_0) \tag{8}$$

$$ASW\,(t) = \int_{t_0}^{t_n} \left[TISF\,(t) + S\,(t) - NSF\,(t) - P\,(t)\right] dt + ASW\,(t_0) \tag{9}$$

$$G - KI\,(t) = \int_{t_0}^{t_n} \left[ASW\,(t) - OTF\,(t) - SWW\,(t)\right] dt + G - KI\,(t_0) \tag{10}$$

$$TIGW\,(t) = \int_{t_0}^{t_n} \left[NIGW\,(t) + RGWF\,(t)\right] dt + TIGW\,(t_0) \tag{11}$$

$$AGW\,(t) = \int_{t_0}^{t_n} \left[TIGW\,(t) + P\,(t) - S\,(t) - OGW\,(t) - E_{GW}\right] dt + AGW\,(t_0) \tag{12}$$

$$WS\,(t) = \int_{t_0}^{t_n} \left[SWW\,(t) + GWE\,(t)\right] dt + WS\,(t_0) \tag{13}$$

Similarly, based on the Stock and Flow Diagram of the socio-political and economic subsystem, population can be formulated as:

$$P(t) = \int_{t_0}^{t_n} \left[PGR(t) \, .P(t-1)\right] dt + P(t_0) \tag{14}$$

where $P(t)$ = population at time t and $PGR(t)$ = population growth rate at time t.

Water consumption (WC) is assumed to be the minimum of water supply (WS) and consumers' water demand (WD):

$$WC = Min. \ \{WS, WD\} \tag{15}$$

The water resource sustainability index (SI) defined by Vojdani and Farhadi (2005) to evaluate the sustainability of water supply (WS) regarding the water demand (WD) is used here. This index is defined as:

$$\text{If} \quad WS > WD, \quad \text{then} \quad SI = (WS - WD)\big/WS \tag{16}$$

$$\text{If} \quad WS \leq WD, \quad \text{then} \quad SI = 0 \tag{17}$$

Based on the preceding equations an increase in water demand decreases the water resource sustainability index while this relation is positive with water supply. Vojdani and Farhadi (2005) suggested that an index greater than 20% belongs to water basins with little or no water stress. In such basins water demand (WD) is less than 80% of water supply (WS). A watershed with a sustainability index (SI) of less than 20% is at significant risk of water stress, depending on local storage and distribution capabilities. The water resources sustainability index has a negative relation with water tension in the watershed. When the aforementioned index decreases, water tension or water conflict appears in the watershed. Assumingly, in such a condition, there would be conflict among different water consuming sectors. The other outcome of existence of water tension can be the appearance of conflicts among neighboring watersheds. Each water basin attempts to allocate more water to itself from the shared resource, which might lead to tragedy of the commons. In the Zayandeh-Rud river basin, for instance, strategists might struggle to increase the incoming transferred flow while they seek to decrease the outgoing transferred flow at the same time. Such strategies have a potential to exacerbate the political relations between the neighboring water basins.

5.2.3 Input Data

A quantitative model with an annual time step is developed and run to assess the Zayandeh-Rud river basin's water resources conditions based on the CLD and the Stock and Flow Diagram of the problem. The geographical boundaries of the model comply with the boundaries of the river basin and the time horizon of the model is 20 years (2006–2025). The ZRW-MSM (Zayandeh-Rud Watershed Management and Sustainability Model) is constructed using STELLA 5.1.1 research software. Because simulation in system dynamics is governed entirely by the passage of time, it is often referred to as time-step simulation. The model takes a number of simulation steps along the time axis. At the end of each step, some model variables, which describe states of the system, are updated to represent consequences from the changes in the previous simulation step.

Evapotranspiration, evaporation from groundwater, natural incoming groundwater, surface water percolation to groundwater, and groundwater seepage are fixed in the model. Initial population and per capita water demands for the year 2006 are set according to the available data. The amount of natural incoming surface water supplied by the Zayandeh-Rud river natural flow is also fixed in the model but can change based on the conditions of different simulation scenarios. The amount of outgoing transferred flow in the model increases according to the watershed's development plans. Surface water and groundwater withdrawal capacities are respectively set to 1,500 mcm (Zayande-Rud Reservoir's capacity) and 3,500 mcm (historic groundwater consumption in the basin), unless they are changed under different scenarios.

The available dynamic model allows experimenting with competing management strategies and evaluation of the comparative strengths and weaknesses of each. Various combinations of hydrological or economic conditions can be simulated using the ZRW-MSM and outputs are generated in seconds. The ultimate objective of a system dynamics study is to comprehend the ongoing problem and the behavior of its corresponding system. To evaluate alternative solutions for improving such behavior, it is crucial to test the model or perform a sensitivity analysis. Accuracy of the model behavior is meaningful only if there is sufficient confidence in the behavior of the model. In testing model's performance, emphasis should be on pattern prediction rather than point prediction, especially when some model parameters have no strong physical basis or are not easily quantifiable, and measurable. The developed model was tested for the period 1997–2002. Lack of data, especially in the socio-political and economic subsystem, was the main reason for the short testing period. The Isfahan Province Management and Planning Organization's population projection data were assumed to be the observed data for population growth. As shown in Fig. 7, the

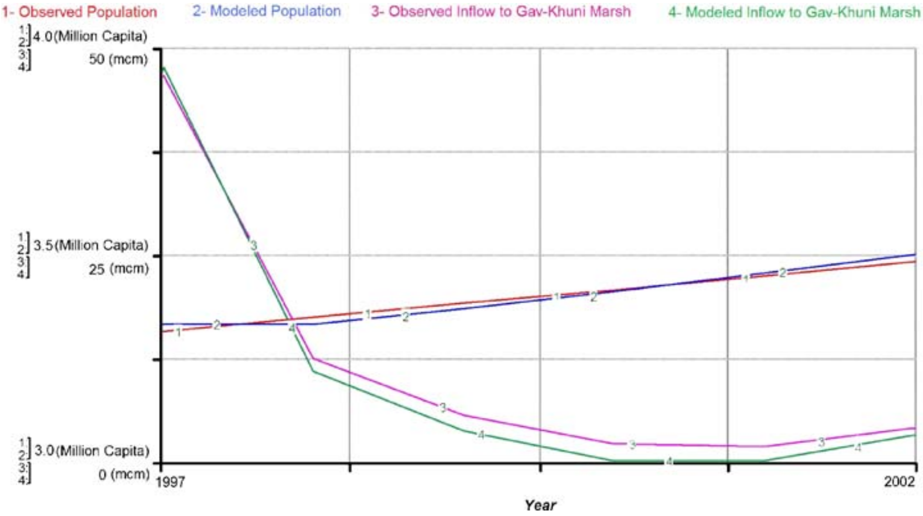


Fig. 7 Comparison of observed data and simulation results

Table 3 Different scenarios and model inputs

Scenario	Input to the model
Business-as-Usual (B.a.U.)	Incoming and outgoing transferred flow increases according to projected watershed plans; groundwater exploitation capacity increases linearly up to 4,000 mcm
Climate Change (C.C.)	Zayandeh-Rud River natural flow decreases linearly as a result of dry climate warming; water transfers similar to B.a.U.; surface water withdrawal remains constant
Population Control (P.C.)	Population remains constant after 2006
Population Control and Demand Management (P.C. and D.M.)	Population similar to P.C.; water demands decrease
Economic Recession (E.R.)	Economic development rate decreases linearly after decrease 2006 until zero in 2025
Increase in Total Surface Water (I.T.S.W.)	Incoming water increases, getting 1,000 mcm more than its amount in 2007 after finalization of third Kuhrang tunnel; surface water withdrawal capacity does not increase
Increase in Total Surface Water and Surface Water Withdrawal (I.T.S.W and S.W.W.)	Increase in total surface water like I.T.S.W.; surface water withdrawal capacity increases linearly, getting 1,000 mcm more than its current amount in 2025
Desirable Future (D.F.)	No change in surface water withdrawal capacity; incoming transferred flow increases linearly, getting 100 mcm more than its current amount in 2006; population growth and water demands similar to P.C. and D.M.

model's backcasting results for inflow to the Gav-Khuni marsh and population for the testing period are satisfactory. There is a small difference between observed data and model's results for the inflow to the Gav-Khuni marsh and the model underestimates this flow after 1998, but behavior prediction of the model is reasonable.

5.2.4 Simulation Scenarios

The model is run to examine the outcomes of eight different water resource plans, strategies, and alternatives for the Zayandeh-Rud river basin. A short description and the main variables of each scenario are presented in Tables 3 and 4, respectively. Basically, the main variables of each scenario are the policy variables which define that scenario (except for the Zayandeh-Rud Natural Flow in the Climate Change scenario).

6 Simulation Results

The model's results for each scenario are shown in Table 5. Figures 8 and 9 clarify the state and sensitivity of the Zayandeh-Rud water resource system to changes in policy variables of each scenario by indicating the behavior of some variables of the

Table 4 Main variables of each scenario

Scenario	Main variable
Business-as-Usual (B.a.U.)	Water transfer Groundwater withdrawal
Climate Change (C.C.)	Zayandeh-Rud natural flow Water transfer Surface water withdrawal
Population Control (P.C.)	Population
Population Control and Demand Management (P.C. and D.M.)	Population Water demand
Economic Recession (E.R.)	Economic development
Increase in Total Surface Water (I.T.S.W.)	Water transfer Surface water withdrawal
Increase in Total Surface Water and Surface Water Withdrawal (I.T.S.W and S.W.W.)	Water transfer Surface water withdrawal
Desirable Future (D.F.)	Water transfer Surface water withdrawal Population Water demand

hydrological and socio-political and economic subsystems. The selected variables from the hydrological subsystem include extra groundwater extraction (the difference between annual groundwater withdrawal and annual groundwater renewal) and inflow to the Gav-Khuni marsh. Water resources sustainability index (*S.I.*), water tension, population, domestic water demand, industrial water demand, agricultural water demand, and total water demand are the selected variables of the socio-political and economic subsystem shown in Figs. 8 and 9.

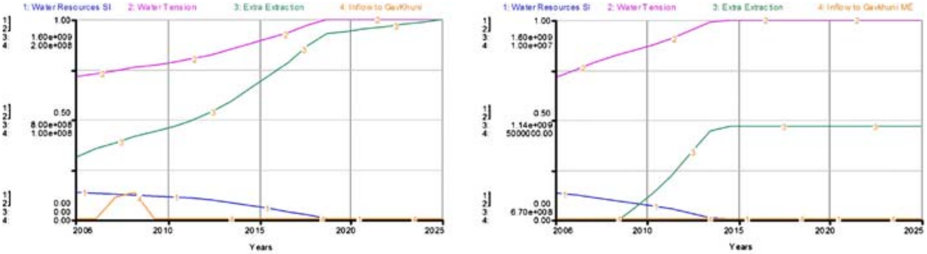
The behavior of different variables of the model in response to changes in the model inputs shows that:

1. Behavior of different model variables in the socio-political and economic subsystem will not change much when water import and water withdrawal capacity increases at the same time.
2. Behavior of population and total water demand graphs are almost the same and highly correlated.
3. Watershed might lose its attraction as a result of low S.I., high water tension, or low economic development rate which reduces immigration and increases emigration.
4. Demand management is really effective in reducing groundwater mining and increasing the flow to the Gav-Khuni marsh. Under most of the scenarios, finalization of the third Kuhrang tunnel in 2007 increases the inflow to the Gav-Khuni marsh for a short period. However, in the long run, when water demand is not controlled, inflow to Gav-Khuni marsh reduces dramatically.
5. In most scenarios, the worst results are inflow to the Gav-Khuni marsh and the extra groundwater extraction, which have tremendous impacts on the Gav-Kuni marsh and groundwater supplies.

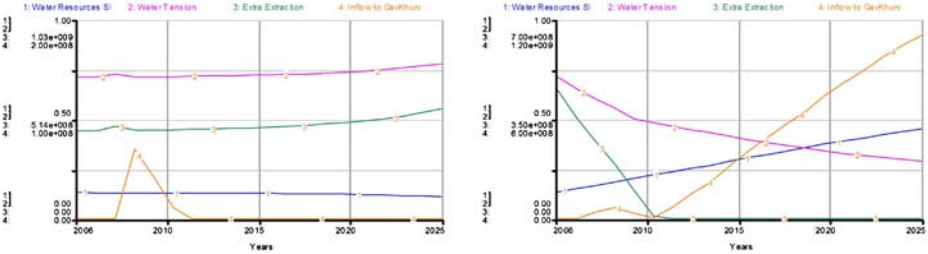
Table 5 Different scenarios and model outputs

Scenario	Model output
B.a.U.	Per capita agricultural water demand does not change; per capita industrial and domestic demands increase; population increase with high growth rate until SI becomes zero, then the growth rate decreases; total water demand changes are identical to population changes; great water tension in the region in the whole period; extra groundwater extraction continues; Gavkhuni Marsh receives no water except in few years following finalization of the third Kuhrang tunnel in which it receives only 20 mcm.
C.C.	Gavkhuni receives no water; water tension increases faster than B.a.U. as a result of low SI; population and water demand do not increase after the second quarter of the simulation period, while the region is suffering from extreme water tension; only in first few years groundwater withdrawal is equal to its renewal, after that groundwater extraction increases rapidly due to increasing water demand until the third quarter of the simulation period when it does not increase because the water demand does not change.
P.C.	Increase in total water demand is lower than C.C.; water sustainability index decreases slightly; water tension does not change much; groundwater extra extraction continues and rises with a higher growth rate in the last quarter of the simulation period; Gav-Khuni Marsh is not supplied with enough water to sustain except a year following the finalization of the third Kuhrang tunnel.
P.C. and D.M.	SI and extra groundwater extraction increases and decreases, respectively; after the second quarter of the simulation period Gav-Khuni Marsh receives enough water for survival.
E.R.	Population and water demand do not increase; groundwater extra extraction, SI, and water tension do not change during this period as a result of constant population and water demand; Gav-Khuni Marsh only receives some water for a limited period after finalization of the third Kuhrang tunnel.
I.T.S.W.	Behavior of all model variables is similar to their behavior in C.C. except the inflow to Gav-Khuni Marsh, which receives enough water for survival.
I.T.S.W and S.W.W.	Behavior of variables are analogous to B.a.U. except the extra groundwater extraction, which in the last years of the simulation period becomes constant due to a balance between water supply and water demand.
D.F.	Model predicts a reduction in water demands; water tension decreases during the simulation period as a result of increase in SI; groundwater withdrawal decreases; Gav-Khuni receives enough water after finalization of the third Kuhrang tunnel.

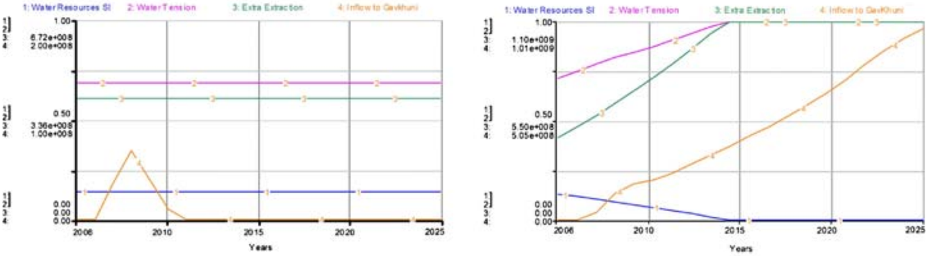
Simulation results indicate how changes in different variables can affect the whole system. Assessment of the model's results for different alternatives present a good perspective of the interconnected and dynamic nature of the system. Quantification of the socio-political and economic subsystem is speculative. However, the main purpose of this study was to comprehend the interactions of different drivers of the problem. This is a quick approach for integrating, exploring, adapting, and understanding the dynamics of the basin. Even if wrong, the developed model can be still useful in early investigation of the interrelationships of the problem drivers.



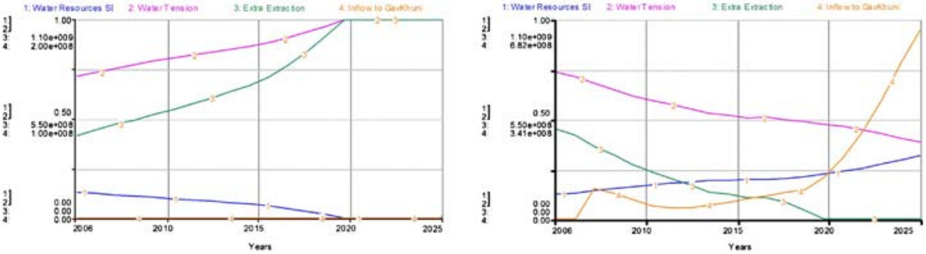
B.a.U. C.C.



P.C. P.C. and D.M.



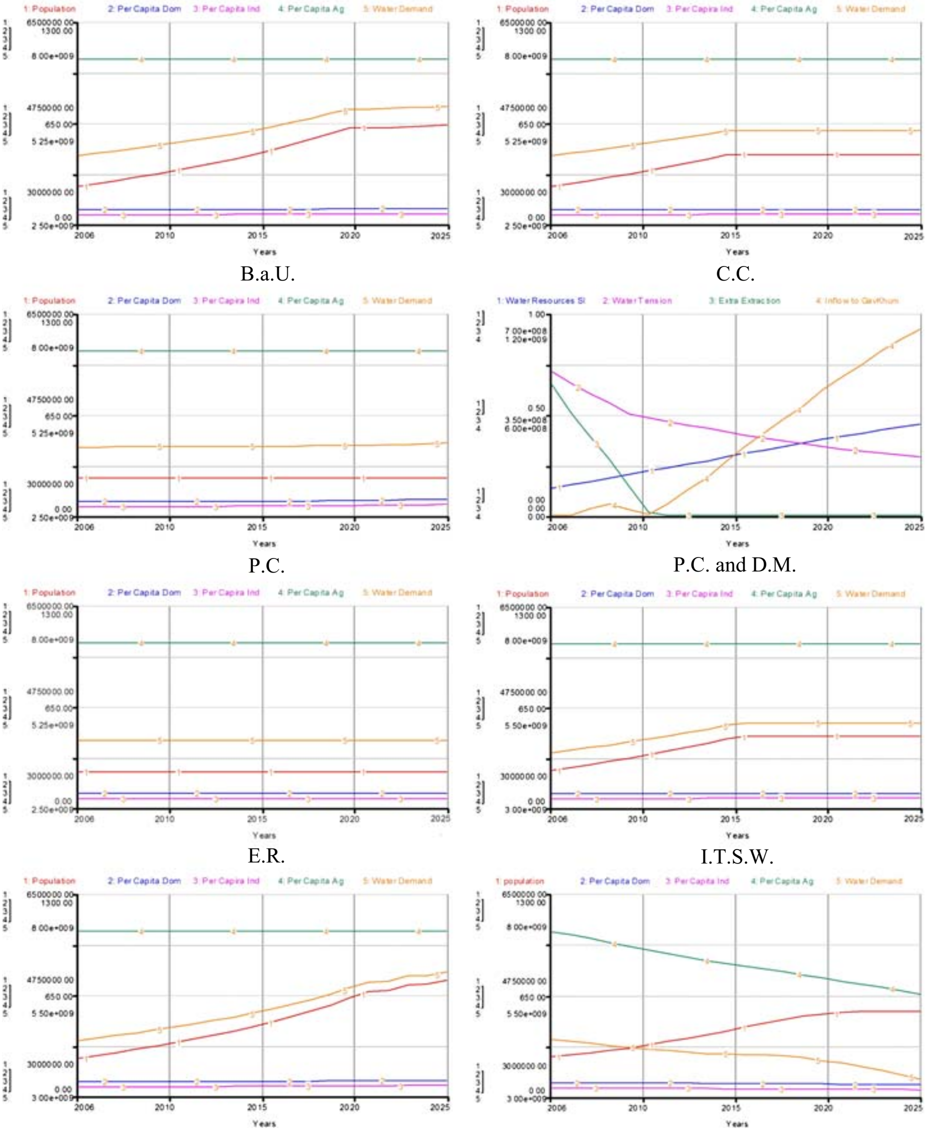
E.R. I.T.S.W.



I.T.S.W and S.W.W. D.F.

Fig. 8 Behavior of selected model's variables under different scenarios (1 Water Resources Sustainability Index (S.I.), 2 water tension, 3 extra groundwater extraction (m^3), 4 inflow to the Gav-Khuni marsh (m^3))

What is important is the behavior of different parameters of the model, not the numbers generated in model runs. Different scenarios were developed merely to comprehend the system behavior. Thus, they are mostly qualitative and may not represent any realistic future.



B.a.U.

C.C.

P.C.

P.C. and D.M.

E.R.

I.T.S.W.

I.T.S.W and S.W.W.

D.F.

Fig. 9 Behavior of selected model’s variables under different scenarios (1 Population (capita), 2 domestic water demand (m^3 per capita), 3 industrial water demand (m^3 per capita), 4 domestic water demand (m^3 per capita), 5 water demand (m^3))

7 Discussion

Results indicate that continuing the management of the Zayandeh-Rud watershed in the same manner (business-as-usual) can have dramatic impacts on the watershed. The studied system showed highly sensitive to water demand and population. The system performance greatly improves, groundwater mining stops, and the Gav-Khuni

Marsh becomes alive again when population growth and water demand are both controlled. Regretfully, Iranian water planners have mostly focused on supplying the residents with more water without paying enough attention to environmental issues. Similar to other places in the world, here water supply planning is based on development and population projections while such conventional projections do not consider the relationship of development and population growth rates with other factors such as water availability. Typically, population and development projections are done by non-water agencies. Such agencies, usually, do not consider water availability as a constraint to development and population growth, and neglect the dynamic interrelations of different variables shown in the CLD of the problem considered herein. This study shows how an integrated planning and consideration of different socio-political and economic elements of the system and their interactions are essential to sustainable water resource management.

Continuation of the current ad-hoc management practice will have a tremendous impact on the Gav-Khuni marsh and groundwater resources. The remedy for Zayandeh-Rud's current problems is not only transferring more water to the basin and increasing the surface water withdrawal capacity. The last fifty years' experiences confirm this fact. As soon as there is an increase in water supply, water demand increases and the water shortage problem is repeated after few years. Increasing water imports when water withdrawal capacities are not controlled and demand management actions are not taken, may only result in residents' false perception of water availability, which can change their expectations, leading to increased water consumption.

The manner in which water resource management is currently practiced in this watershed must be rectified. Water transfer and increase in surface water withdrawal capacity is only a short-run remedy for the problem and an escape from water tension for a few years, which only postpone water shortage. To have sustainable water resources, attention must be paid to all aspects of the system, not only attempting to supply the residents with water while neglecting other drivers of the problem.

8 Concluding Remarks

The purpose of the system dynamics approach presented here was to provide an experimental simulation platform for the analysis of an interconnected strategic problem in its interconnected context. The objective was to test the policies/strategies that address the issues of demand management, water transfers, economic and industrial development, and environment and population dynamics.

The CLD developed in this study provides a good perspective of the Zayandeh-Rud watershed problem as well as different drivers of the system and their interconnected relations. Being aware of these relations, strategists can make decisions to rectify the current system. System dynamics simulation allows evaluation of regional solutions and can provide answers to different strategic questions. The quantitative model, ZRW-MSM together with the CLD of the problem, helps us better understand the problem and predict the behavior pattern of different variables of the system over time based on different decisional inputs to the system. By considering probable behavior of different variables in regard to different strategies, water planners can make best decisions taking into account hydrological, environmental, socio-political, and economic aspects of water resource development plans.

No model is perfect and all models have some limitation which should be taken into account while results are interpreted. The current version of ZRW-MSM has been built and calibrated based on limited available data sets but it can be helpful in better understanding and validating the CLD of the problem. Quantification of the socio-political elements of the model is very speculative and challenging. Nevertheless, since the main goal of studies like this is to comprehend the interactions of different drivers of the problem, the available model, even if wrong, can be still useful in early investigations of the system responses to different plans and strategies. This is valuable as a quick approach for integrating, exploring, adapting, and understanding dynamics of the watershed. In an engineering model with socio-economic variables, the emphasis should be on pattern recognition, not the numbers generated in different model runs. Here, different scenarios, which are mostly qualitative, were developed merely to comprehend the system behavior and may not represent any realistic future. It is expected that the developed and modified version of ZRW-MSM would contribute to the development of new policy options, structural, and non-structural water solutions (from planning new systems to operating existing ones) and sustainable water resource management in the basin.

The Zayandeh-Rud river basin can pay for water resource management or it can pay more for mismanagement. No single solution will fix the Zayandeh-Rud watershed's water problems. A combination of approaches is called for, and several areas of action should be considered to address multiple weaknesses in the current water resource management system: Model's results for different water resource plans and scenarios showed that the Zayandeh-Rud watershed's current problems cannot be solved merely by increasing water imports and withdrawal capacities. Thus, water planners of this Iranian strategic watershed should change their last decades' main policy and look for better solutions, considering the model results in addition to the CLD of the problem. Such solutions may include water demand management, population control, and increased water imports when water withdrawal is controlled. Those solutions may lead to: (1) sustainable development of water resources having water supplies exceeding demands over long periods; (2) sustainable groundwater without mining the resource by having groundwater withdrawals less than or equal to the basin's safe yield; (3) conservation of environmental resources and ecosystem (e.g., Gav-Khuni marsh); and (4) keeping the watershed out of water tension, without competition among different water consuming sectors and conflicts with neighboring watersheds over shared water resources.

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