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Research article

System dynamics simulation of regional water supply and demand using a food-energy-water nexus approach: Application to Qazvin Plain, Iran

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ABSTRACT

Understanding the complexity and feedbacks among food, energy, and water (FEW) systems is key to making informed decisions about sustainable development. This paper presents qualitative representation and quantitative system dynamics simulation of the water resources system in the Qazvin Plain, Iran, taking into account the energy intensity of water supply and interconnected water use sectors (e.g., urban, industrial, and agricultural). Qazvin Plain faces water resources challenges that are common to arid/semi-arid areas, including frequent droughts, declining surface water and groundwater, and increased urban and agricultural water demand. A system dynamics model is developed using historical data (2006–2016) to investigate the effects of anticipated dynamics of integrated water and energy sectors in the next two decades. The results of policy scenarios (2020–2039) demonstrate that the continuation of the existing management policies will cause severe damage to the water and energy sectors, pushing the system towards water resources limits to growth. An annual groundwater table decline of nearly 1 m is anticipated, indicating significant overshoot of the plain's natural recharge capacity, which may lead to the depletion of recoverable groundwater in the plain within the next three decades. The groundwater table decline will cause energy consumption of water supply to increase by about 32% (i.e., 380 GWh) to maintain irrigated agriculture. It is critical to implement a combination of water demand and supply management policies (e.g., net agricultural water savings and recycling treated wastewater) to delay the problem of water limits to growth in the region.

Author contribution

Mohammad Mahdi Naderi: Software, Validation, Writing – original draft, Ali Mirchi: Methodology, Validation, Project administration. Ali Reza Massah Bavani: Software, Supervision, Investigation. Erfan Goharian: Conceptualization, Writing-Reviewing and Editing. Kaveh Madani: Formal analysis,Writing- Reviewing and Editing.

1. Introduction

The last couple of decades have witnessed a growing recognition of the inextricable interconnections of food, energy, and water (FEW) sectors (Bazilian et al., 2011; Scanlon et al., 2017; Cai et al., 2018; Bogardi et al., 2012; Ringler et al., 2013; Madani and Shafiee-Jood, 2020) This recognition has sparked interest to better understand various linkages between water-energy (Stillwell, 2010; USGS 2015; Madani and Khatami 2015), food-water (Kumar et al., 2012), and food-energy (DeNooyer et al., 2016; Sanders and Masri, 2016; Zhang and Vesselinov, 2016), as well as the FEW nexus (Biggs et al., 2015; Liu et al., 2015; Jalilov et al., 2016; White et al., 2018; Mirzaei et al., 2019). The FEW nexus concept presents challenges and opportunities for water resources management in the transition to a holistic resource management paradigm (Scanlon et al., 2015; Cai et al., 2018) to enhance water, energy and food security through synergistic development strategies and

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management policies, and improved governance among the three sectors (Hoff, 2011).

The FEW nexus management challenges are dire in arid/semi-arid regions such as vast areas of Iran due to renewable water scarcity, which, in turn, can limit food production unless ample groundwater and energy resources are affordably available to maintain agricultural operations. Iran is actively implementing a supply-oriented water management strategy by expanding surface water resources through dam construction and water transfer projects (Madani, 2014). Groundwater is used to compensate for surface water shortage, a common practice in water scarce regions around the world. Consequently, Iran's groundwater resources are generally declining across the country, increasing the energy consumption to lift deeper groundwater (Mirzaei et al., 2019) to maintain food production (Maghrebi et al., 2020) and protect rural employment in the agricultural sector. Overpumping of aquifers for agricultural water supply coupled with population growth are among key reasons for dwindling groundwater availability in different parts of Iran (Karimi et al., 2012; Madani et al., 2016; Ashraf et al., 2017).

Integrated models and performance assessment frameworks can help operationalize the FEW nexus concept to guide sustainable development (Endo et al., 2017). System dynamics modeling is a simulation approach that can facilitate investigating FEW nexus questions by conceptualizing non-linear causal links and feedback relationships among interconnected sub-systems within specified system boundaries (Forrester 1968, 1970; Sterman 2000; Hjorth and Bagheri, 2006). It has been applied in water resources and environmental studies (Winz et al., 2009; Mirchi et al., 2012), food systems (Georgiadis et al., 2005; Xu and Szmerekovsky, 2017), and energy systems (Ahmad et al., 2016; Leopold, 2016; Fontes and Freires 2018). System dynamics models of water resources systems consisting of multiple sub-systems and linkages with other resource management issues cover a wide range of scales. These applications include global scale water dynamics and its connection to drivers of industrial growth (e.g., population, agriculture, economy, non-renewable resources, and environmental pollution (Simonovic, 2002); national level evaluation of FEW interactions for crop and consumption taking into account virtual water and energy import and export and water and energy footprints (El Gafy et al., 2016); basin scale representation of water resources and management policies that drive socio-economic and agricultural development (Gohari et al., 2013; Madani and Eslami, 2005) and household level analysis of the FEW demand and associated wastewater and organic waste based on a host of behavioral, socio-economic and technological factors (Hussien et al., 2017).

In this paper, we apply system dynamics simulation to investigate water management strategies in the Qazvin Plain, Iran, using a FEW nexus approach. Previous applications of system dynamics simulation demonstrated the weaknesses of the dominant supply-oriented water management, which has caused critical unintended consequences by overlooking feedback effects of increasing water supply as a driver of future demand (Madani and Mariño 2009; Gohari et al. 2013, 2017). The present system dynamics model advances previous applications by quantifying the energy implications of water supply with respect to changes of interlinked FEW variables under alternative management scenarios. To this end, we use the concept of average energy intensity of water supply, i.e., energy consumption to supply a unit volume of water to meet sectoral demands within a water basin. The model provides a high-level representation of different FEW sub-systems in the study area, namely production of major crops, water supply and demand, urban wastewater system, population, and energy use. We evaluate the impacts of changes in irrigation efficiency, crop pattern, pump efficiency, and dam building on both water consumption and energy needed for water supply to examine FEW nexus based policies that can potentially mitigate groundwater depletion and reduce the energy footprint of water supply.

2. Qazvin Plain, Iran

Qazvin Plain occupies about 9500 km^2 of the Namak Lake basin, Iran (Fig. 1). The region has an arid and semi-arid climate with an average precipitation of about 256 mm/year. Qazvin plain contains an extensive network of irrigation canals that serve about 80,000 ha in the northern part of the plain (Vaez Tehrani et al., 2013). Agricultural water is supplied from a combination of groundwater (e.g., local wells, qanats (i.e., gently sloping underground galleries that transfer groundwater), and springs) and surface water transfer from Taleghan Reservoir (between 100 million cubic meters (MCM) to 330 MCM per year in recent years). In addition, Haji Arab and Khar Rud Rivers, with the average annual flows of 28 and 149 MCM, respectively, are two major unregulated, ephemeral rivers that are used periodically to supply additional agricultural water. The plain is underlain by Qazvin Aquifer, one of the largest unconfined aquifers in Iran, providing more than 1.6 billion cubic meters of water, mostly for agricultural use. Overexploitation of the aquifer has caused a significant drop in the groundwater level in the region. Nohob Dam (capacity: 38.5 MCM) on Haji Arab River and Balakhanlou Dam (capacity: 120 MCM) on Khar Rud River are planned for construction to reduce the pressure on the aquifer and prevent further depletion of the groundwater storage. Furthermore, new irrigation networks are planned to modernize agricultural water supply. Table 1 summarizes key water resources characteristics of the Qazvin Plain.

3. System dynamics model

The Qazvin Plain provides geographic boundaries of the current system dynamics model. Within the plain, the model consists of four interconnected sub-systems to conceptualize the basin-level system structure capturing FEW nexus interactions. The sub-systems are (1) hydrology, water, and wastewater (Gohari et al., 2013); (2) population; (3) agriculture; and (4) energy. The model also uses a number of exogenous variables such as surface water inflow from neighboring basins, precipitation and temperature. Causal loop diagrams were drawn using a combination of variables and polarized arrows to illustrate a positive (change in the same direction) or negative relation, indicating change in opposite direction (Sterman, 2002). CLDs of the four sub-systems illustrate the interactions and feedback relationships between different sub-systems in the Qazvin Plain (Fig. S15-S18 in Supplementary Materials (SM)). Using Vensim DSS (Ventana Systems, 2003), the CLDs were integrated and converted into a stock-and-flow (SFD) model to perform simulations. A stock and flow diagram (SFD) consists four different elements: (1) stocks, which represent accumulations and depletions through time; (2) flows defined as rate at which stocks change at any given instant); converters, which take inputs and convert them into output signals; (4) connections, which capture interlinkages among different parts of the system. In summary, CLDs and SFD are used in water resources system dynamics modeling to visualize, analyze and simulate a system in a quantitative way (Hjorth and Bagheri, 2006; Mirchi et al., 2012).

3.1. Hydrological, water, and wastewater sub-system

Interactions between regional hydrologic processes, surface water and groundwater, water allocation, and wastewater collection are captured in the stock and flow diagram (SFD) of the hydrological, water, and wastewater sub-system (Fig. 2). A number of regional hydrologic variables such as precipitation, temperature, natural inter-basin flow from adjacent basins, as well as wastewater collection and treatment sub-system components are included as exogenous variables. This is a simplification based on the assumption that the exogenous variables do not change directly in response to feedback effects within the sub-system, although they affect the endogenous components of the sub-system. This simplification is necessary from a practical modeling

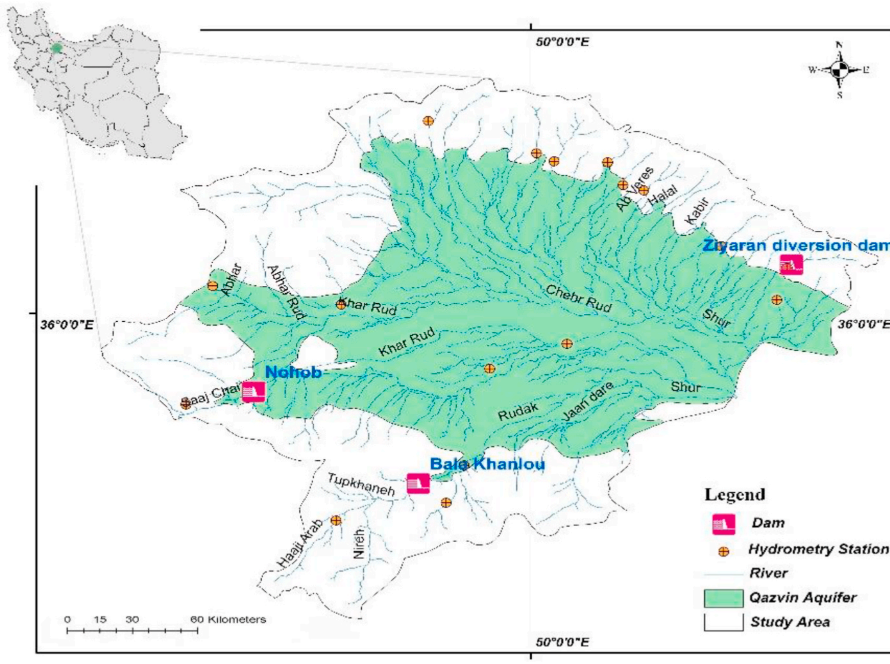

Fig. 1. The geographic location of Qazvin Plain in Iran.

Table 1
General characteristics of the Qazvin Plain.

Attribute	Value
Geographic and hydrologic	
Area of plain (km^2)	9501
Annual average precipitation range (mm)	250–500
Annual average evaporation range (mm)	1800–2600
Average transferred flow (MCM)	100–330
Annual average surface runoff (MCM)	275
Elevation range (m)	1130–4175
Groundwater	
Number of registered wells	7881
Average groundwater drawdown per year (m)	1.01
Water supply from groundwater (%)	67
Groundwater supply from wells (%)	94
Groundwater supply from qanats[a] (%)	4
Groundwater supply from springs (%)	2
Municipal	
Per capita municipal water demand in 2006[b] (liter/day)	176
Municipal water use (%)	5
Water supply from groundwater (%)	100
Life expectancy in 2006[b] (years)	72
Agriculture	
Water supply from groundwater (%)(2006–2016)	77–88
Irrigated land area (ha)	167,370
Irrigation efficiency (%)	28.0–41.1
Agriculture water use (%)	93
Industrial	
Water supply from groundwater (%)	100
Industrial water use (%)	2
Wastewater treatment plant	
Sewage system coverage in 2006[b] (%)	49
Energy consumption to treat wastewater (KWh/m^3)	0.06

[a] Ancient underground aqueducts that transfer groundwater to the earth surface under gravitational force.
[b] Start of the simulation period in the calibration process.

standpoint. For example, abrupt changes in water management policies cannot be ruled out or extreme precipitation and droughts may occur in the future. However, it is difficult, if not impossible, to link those directly to dynamic changes within the basin, which complicates quantitate simulations.

Irrigated agriculture is the biggest water user (>90%) followed by municipal (5%) and industrial sectors (2%) in the Qazvin Plain. The proportion of surface water withdrawal is relatively small compared to groundwater pumping due to the low annual discharge of ephemeral streams in the Qazvin Plain. Surface water has been exclusively allocated to irrigate croplands and orchards. Transferred flow is an additional source of agricultural water supply through an extensive irrigation network downstream of the Taleghan Dam (Orojloo et al., 2018; Vaez Tehrani et al., 2013). Ziyaran diversion dam conveys more than 100 MCM of water each year from Taleghan Dam. The general principle for the water allocation in this region is that municipal, industrial, and agricultural users have sequential priorities. About 5.4 MCM/yr is allocated for environmental flows.

While wastewater collection and treatment is not currently implemented in the basin, this study examines this scenario assuming wastewater collection and treatment will be completed by 2040. Implementing the wastewater collection system is expected to decrease the amount of Qazvin Aquifer recharge after shutting down the wastewater disposal wells that are currently used, reducing sewage contamination of groundwater storage. Treated wastewater will be available for irrigation to improve the reliability of agricultural water supply.

Equation (1) below represents the groundwater storage, as the main stock in the hydrological, water, and wastewater sub-system:

$$GWS = \int_{t0}^{tn} [GI(t) + DI(t) - E(t) - GW(t) - GO(t)] \quad (1)$$

Where *GWS* is groundwater storage, t is time ($t_0 \leq t \leq t_n$), *GI* is the sum of natural groundwater inflow and return flow, *DI* is deep infiltration from precipitation, *ET* is evapotranspiration, *GW* is groundwater withdrawal, and *GO* is groundwater outflow from the basin.

3.2. Population sub-system

The SFD of the population sub-system (Fig. 3) was constructed based on the WORLD3 concept (Meadows et al, 1974, 1992). The WORLD3 population model involves the aging chain of the population between four specific age groups, namely children (0–14), adolescents (15–44), adults (45–64), and older adults (above 65). Mortality rate of each age

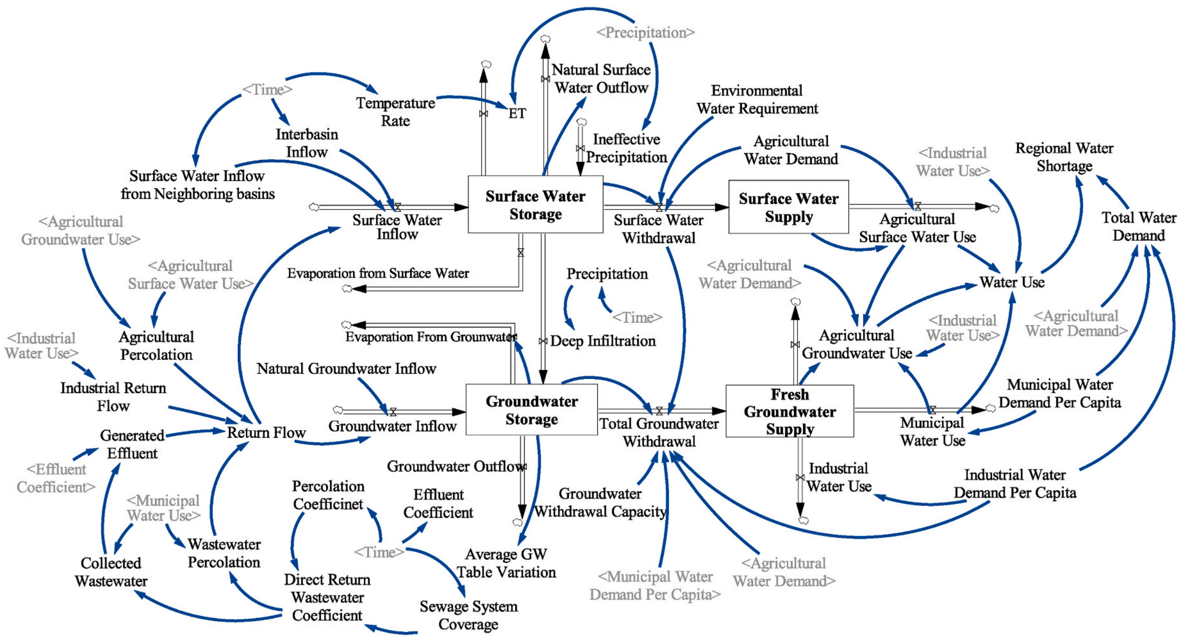

Fig. 2. Stock and flow diagram of the hydrological, water, and wastewater sub-system (adapted from Gohari et al., 2013).

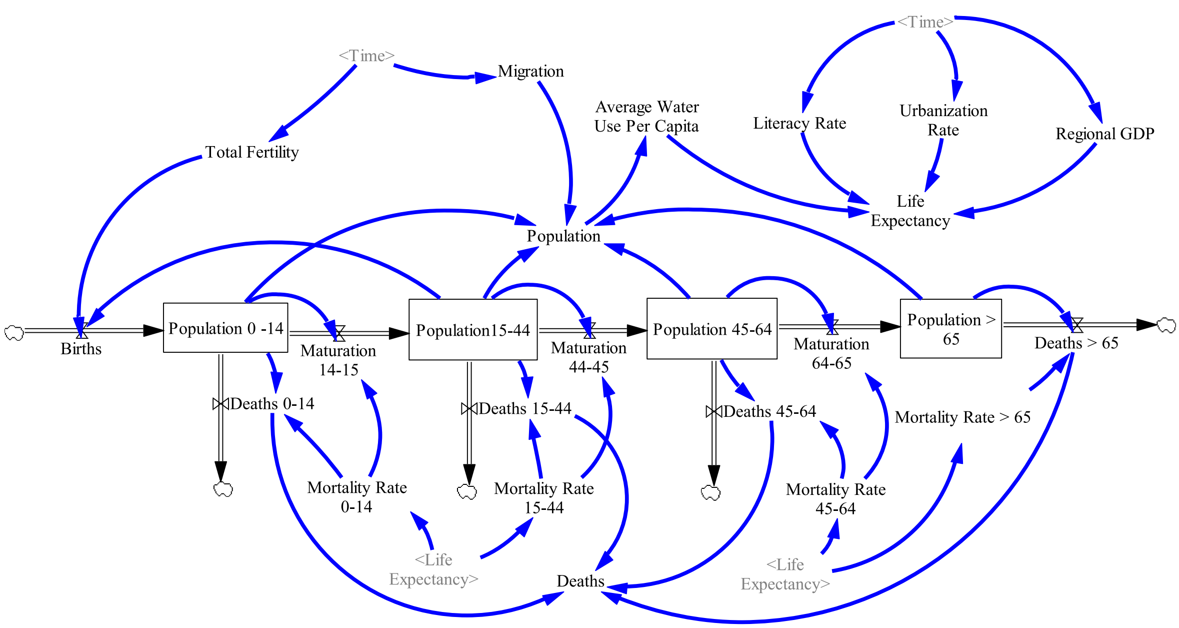

Fig. 3. Stock and flow diagram of the population sub-system.

group is a function of life expectancy as detailed in Section 4 of the SM. Average life expectancy is a function of literacy rate, regional gross domestic product (RGDP), urbanization rate, and the average water use per capita. As these socio-economic factors change through time, different life expectancies adjust the rates of birth and death. For example, the increase in average water use per capita has a positive effect on life expectancy, thereby increasing population growth and total water demand. This triggers a reinforcing feedback behavior that leads to increased water demand and supply, and as a result, more energy consumption for supplying the required water (see Fig. S1 and S18 in SM). The total number of deaths in each age group is governed by the corresponding mortality rate. The birth rate is a function of the fertility rate, which is an important factor for population growth. Migration is considered as an exogenous input based on available census data. Maturation flows show the transition of population from one age group to the next (Meadows et al., 1992). Life expectancy is calculated using a multivariate linear regression:

$$LE = \left[\left(5.38 \times 10^{-6}\right) \times RGDP\right] + \left[\left(2.68 \times 10^{-3}\right) \times AWUC\right] + \left[0.129 \times UR\right] + \left[164.7 \times LR\right] \quad (2)$$

where *LE* is life expectancy, *RGDP* is regional *GDP*, *AWUC* is average water use per capita, *UR* is urbanization rate, and *LR* is literacy rate obtained from census of the Statistical Center of Iran. The Coefficient of Determination (R^2) and Standard Error (SE) for the above multiple linear regression (MLR) were 0.98 and 0.14, respectively. Also, p-values for all parameters were below 0.05, indicating their statistical significance.

Total annual deaths is calculated as follows (Eq. (3)):

$$TD = \left[\left(Pop_{(0-14)} \times Mortality_{(0-14)}\right) + \left(Pop_{(15-44)} \times Mortality_{(15-44)}\right) + \left(Pop_{(45-64)} \times Mortality_{(45-64)}\right) + \left(Pop_{plus\ 65} \times Mortality_{plus\ 65}\right)\right] \tag{3}$$

3.3. Agricultural sub-system

The agricultural sector uses more than 90% of available water in the Qazvin Plain to produce wheat, barley, alfalfa, maize, potato, vegetables, sugar beet, and orchard products. The agricultural sub-system was conceptualized using auxiliary variables (Fig. 4). For simplicity, four major crops with the highest amount of annual water consumption (i.e., alfalfa, barley, maize, and barley) were considered in this study. In addition, it was assumed that the rest of the agricultural water supply is used to meet the water demand of orchards. The cultivated area for each crop was estimated based on the long-term average annual cultivated land area, assuming that agricultural water savings will not lead to the expansion of irrigated lands. This is a critical assumption, which basically means coordinated management of water and agricultural lands, i.e., reducing agricultural water quotas concurrent with increasing irrigation efficiency to avoid the counterintuitive result of increased water demand/consumption as a result of increasing irrigation efficiency (Perry et al., 2017).

Net irrigation water requirement for each crop is annually estimated based on cultivated land area and net water requirement of each crop per hectare (Fig. S2-S5 and Section 4 in SM). Total expected agricultural water demand was calculated as the sum of the gross water requirements of the four major crops and orchards. Irrigation efficiency has a negative relationship with gross water requirements of crops (Fig. S16 in SM). So, improving irrigation efficiency will reduce gross water requirements, decreasing total agricultural water demand if water savings are not used to expand irrigated lands, especially for producing water-intensive crops. The actual crop yield is a function of percent of agricultural water used for each crop, maximum expected yield, agricultural water use and gross water requirement for each crop. Thus, water shortage can adversely affect the agricultural sub-system and endanger the production of various crops. The agro-ecological zones (AEZ) method, developed by the Food and Agricultural Organization (FAO) with the collaboration of the International Institute for Applied Systems Analysis (IIASA)(Alexandratos and Bruinsma, 2012) was used to estimate the net irrigation water requirement and also the maximum expected yield of different crops. Equations (4) and (5) below represent the annual gross water requirement for each crop and annual agricultural water demand, respectively:

$$GWR_i(t) = \frac{NIWR_i(t)}{IE} \tag{4}$$

$$AWD_t = \sum_{i=1}^{n} GWR_i(t) \tag{5}$$

where $GWR_i(t)$ is gross water requirement for crop (i), $NIWR_i(t)$ is net irrigation water requirement of crop (i), and *IE* is irrigation efficiency of crop (i) in year (t). AWD_t represents the annual agricultural water demand in year (t).

3.4. Energy sub-system

The energy sub-system (Fig. 5) estimates the energy needed to provide water for stakeholders and calculates the energy demand of urban wastewater treatment plants. This sub-system, too, was conceptualized using auxiliary variables. More than 70% of the total water supply in the Qazvin Plain comes from groundwater storage. Energy consumption for water supply varies annually and it highly depends on the quantity of extracted water and depth of operational wells. There is a positive relationship between agricultural water use for irrigation and groundwater table. The larger the number of irrigated fields, the greater the groundwater table decline will be because groundwater is the dominant water source and agricultural percolation is small. The required energy to pump groundwater will increase as the groundwater table declines. Groundwater has been extracted from wells scattered throughout the plain. Based on the negative causal relationship between water demand

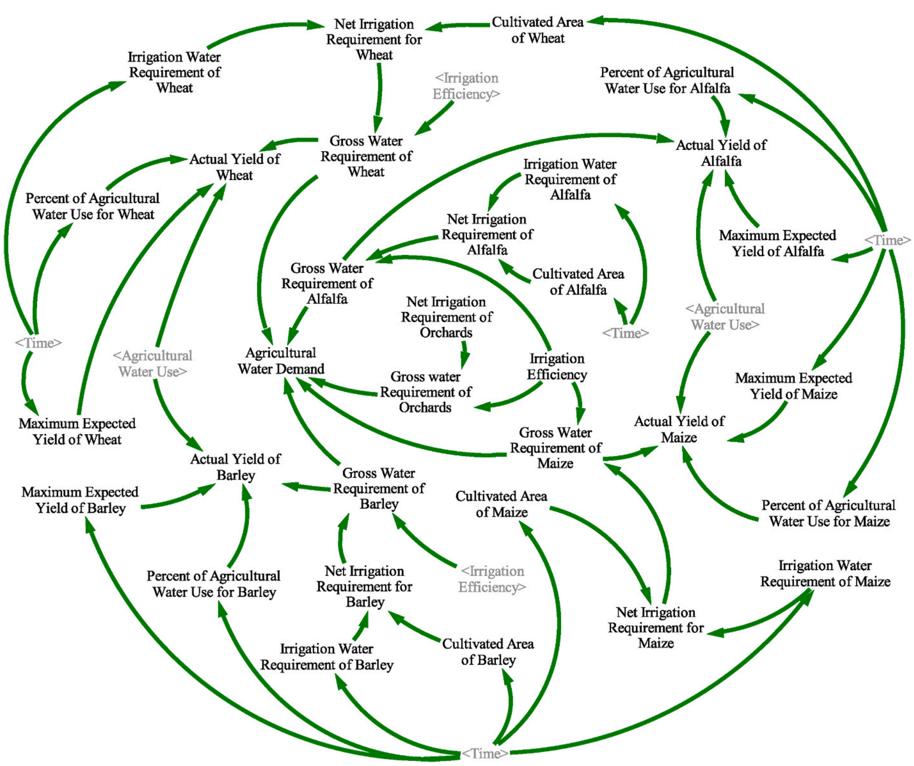

Fig. 4. Conceptual model of the agricultural sub-system.

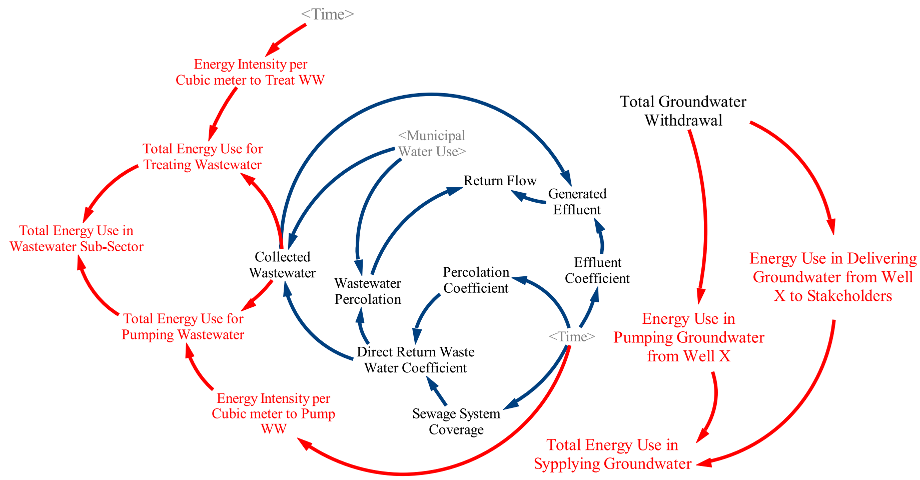

Fig. 5. Conceptual model of the energy sub-system, including reuse of treated wastewater. (arrows shown in dark blue and red represent causal relations of hydrological, water and wastewater, and energy sub-systems, respectively). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and groundwater table, more pumping means more decrease in the aquifer water table and more energy consumption for extracting water from deeper levels for delivery to water users (Moazedi et al., 2011). Energy consumption to lift groundwater was calculated based on Equation (6) (Karimi, 2011).

$$EC = \frac{2.73 \times D \times V}{OPE \times (1 - Tl) \times 1000} \tag{6}$$

Where EC is energy consumption (KWh), D is lifting height (m), V is volume (m^3), OPE is the overall pumping plant efficiency (about 40% in Iran), and Tl is the percent of energy lost in transmission and distribution (only in case of electric pumps otherwise 0).

Wastewater treatment plants use a significant amount of energy for pumping and recycling the collected wastewater (Lin et al., 2009; Plappally, 2012). In order to simplify the energy sub-system in the present system dynamics model, the treatment process was broken into pumping and treatment stages (Fig. 5). Despite causing groundwater pollution, traditional municipal septic systems recharge the aquifer. The planned municipal wastewater collection networks in the Qazvin plain will reduce the percolation coefficient of municipal wastewater, gradually decreasing the amount of return flow until 2040. The plain contains multiple urban areas whose sewage systems have been expanded with the growth of the cities. The energy required to recycle wastewater increases commensurately with growing municipal water demand. This means that these positive causal relationships will dominate the overall behavior of the energy sub-system by activating a reinforcing feedback, which significantly increases the required energy for water supply in the future.

3.5. Simplified stock-and-flow model

The simplified SFD of the system integrates the hydrological and water/wastewater, population, agricultural, and energy use subsystems (Fig. 6). Each stock represents an ordinary nonlinear differential equation solved using a numerical integration method such as the Euler's technique, which was used in this application. Detailed description of

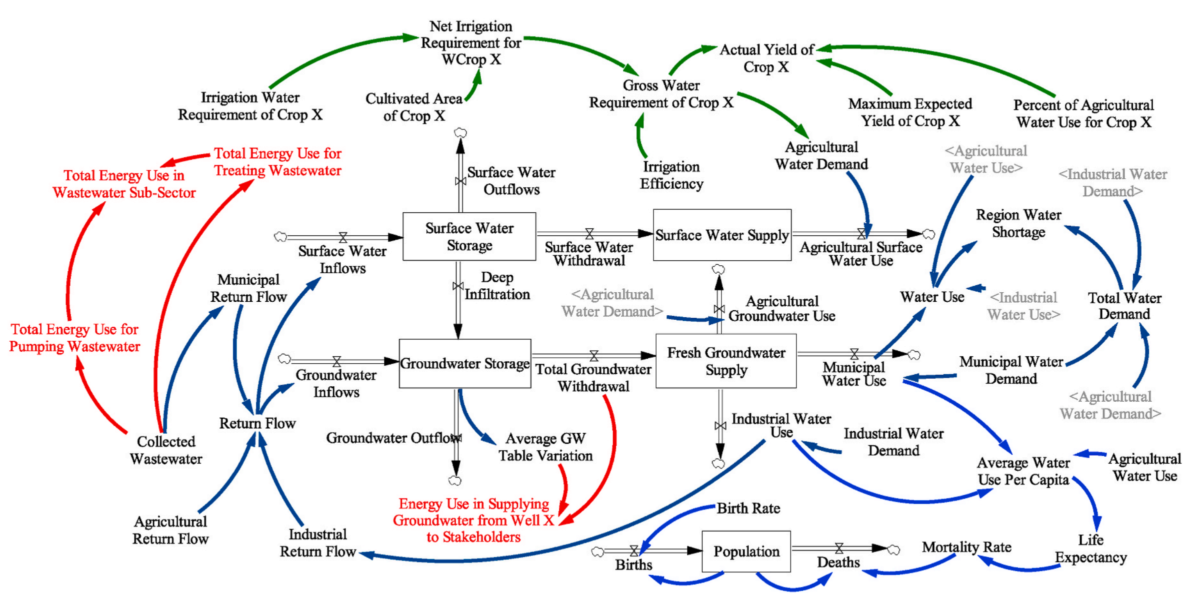

Fig. 6. The stock and flow diagram of the FEW system dynamics model of the Qazvin Plain (arrows shown in dark blue, red, green and blue represent causal relations of hydrological, water and wastewater, energy, agricultural, and population sub-systems, respectively). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

equations, units, etc, for different components of the SFD are provided in the SM. The SFD development process was guided by input from experts from the Regional Water Authority of Qazvin and Iran Ministry of Agriculture-Jahad. We incorporated expert input when building the CLDs of the sub-systems to ensure realistic understanding of the system structure and interactions among different sub-systems (Fig. S15-S18 in SM).

Stocks, such as surface water storage, groundwater storage and population represent the system's states, which will change through time by changes in inflows and outflows. The flows are shown by pipes with a valve pointing into or out of the stocks. Due to the large number of wells, numerical calculations of energy consumption for pumping groundwater and its distribution are not shown in the SFD of energy sub-system. The total energy use to pump and deliver groundwater to stakeholders is calculated as a summation of estimated energy consumption at each well based on the annual groundwater withdrawal and groundwater table (see Fig. S19 in SM for details). The two dynamic feedback loops between water and wastewater sub-system and agricultural and population sub-systems illustrate how the water resources sector meets the demands of local stakeholders. Consequently, groundwater storage as the main source of water in the area will be gradually depleted and more energy will be to supply water and treat wastewater in the future.

4. Model calibration and performance evaluation

The performance of the system dynamics model was evaluated by direct structural tests and structurally-oriented behavior replication tests (Barlas, 1996). Direct structural tests include dimensional consistency of equations and ensuring the defined system boundaries and sub-system components are adequate for intended policy assessments (see Section 6). Structurally-oriented behavior test was conducted by applying extreme conditions. For example, changes of aquifer storage in "no surface water withdrawal" condition was compared with business as usual to ensure if the system's patterns are consistent. Once the system structure was verified, the system level behavioral patterns under status quo baseline condition were compared against observational records.

The comparison of simulated and observed (2006–2016) values of average groundwater table, population, municipal energy consumption for pumping water, and actual wheat yield in the plain. Maximum relative error (M), coefficient of determination (R^2), and discrepancy coefficient (U_0) were used for quantitative evaluation of model performance. Maximum relative error (Eq. (7)) calculates the possible divergence between the observed and simulated data, describing the worst model performance. The ranges of maximum relative error (M) in each year (2006–2016) for population, collected wastewater, average actual wheat yield, municipal energy use in pumping water, and average groundwater table variation were −0.008–0.015, −0.111–0.113, −0.072–0.045, −0.136–0.157 and −1.06–0.863, respectively. The coefficient of determination (Eq. (8)) is the proportion of variance in the observed data that is predictable from the simulated data (Moriasi et al., 2007). The discrepancy coefficient (Eq. (9)) is a "summarizing and reporting tool" in the last step of behavior evaluation (Barlas, 1989), which ranges from 0 (perfect simulation) to 1 (inferior simulation) based on the agreement between the observed and simulated values. The coefficient of determination (R^2) and discrepancy coefficient (U_0) for selected model variables are reported in Fig. 7.

$$M = \frac{\sum (Y_{sim} - Y_{obs})}{\sum Y_{obs}} \tag{7}$$

$$R^2 = \left(\frac{Cov(Y_{sim} - Y_{obs})}{\sigma Y_{sim} - \sigma Y_{obs}} \right)^2 \tag{8}$$

$$U_o = \frac{\sqrt{\sum (Y_{sim} - Y_{obs})^2}}{\sqrt{\sum Y_{sim}^2 + \sum Y_{obs}^2}} \tag{9}$$

where Y_{sim} and Y_{obs} are the simulated and observed data point for the tested parameter, respectively; $Cov(Y_{sim}, Y_{obs})$ is the covariance of the simulated and observed data; and σY_{sim} and σY_{obs} are the standard deviations of simulated and observed sets of values.

Extreme condition tests were performed to evaluate how changing different parameters would affect model behavior (Sterman, 2000). Extreme conditions used in this study were extremely large population growth (i.e., population growth rate tripled by 2016) and no surface water withdrawal. Selected model parameters were set to extreme values during the simulation period. Subsequently, the impacts of these changes were investigated on available surface water storage, groundwater storage, municipal water use and collected wastewater (Fig. 8). Assuming constant per capita water demand, the results show increases in municipal water use, collected wastewater, and total energy demand in wastewater treatment under extreme population growth compared to the baseline scenario. In the case of no surface water withdrawal, surface water storage continuously increases after 2008, while groundwater

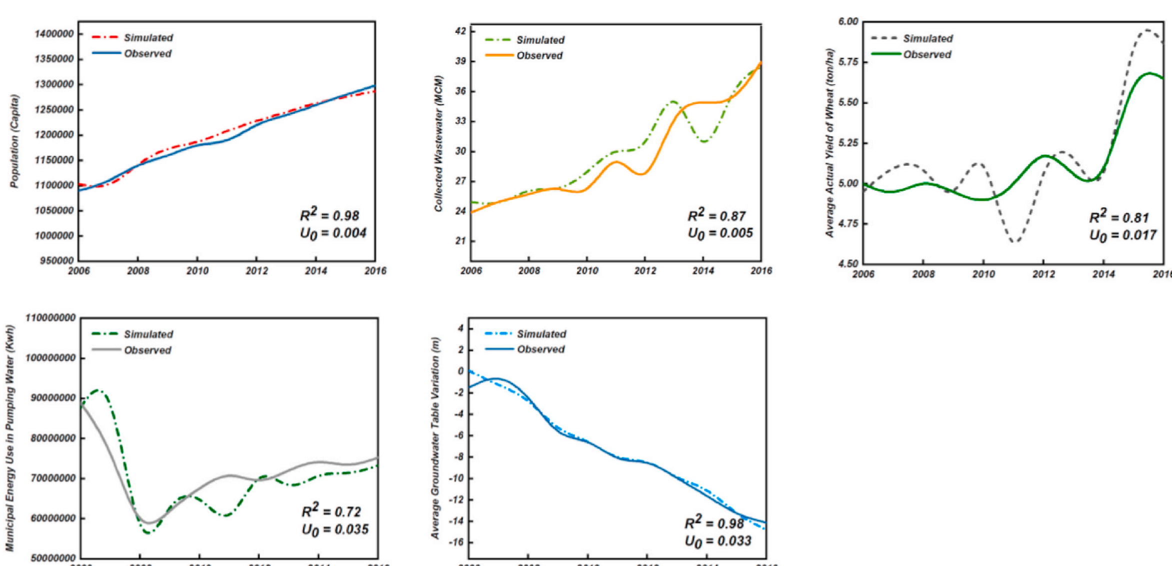

Fig. 7. The comparison of model simulations with observational data.

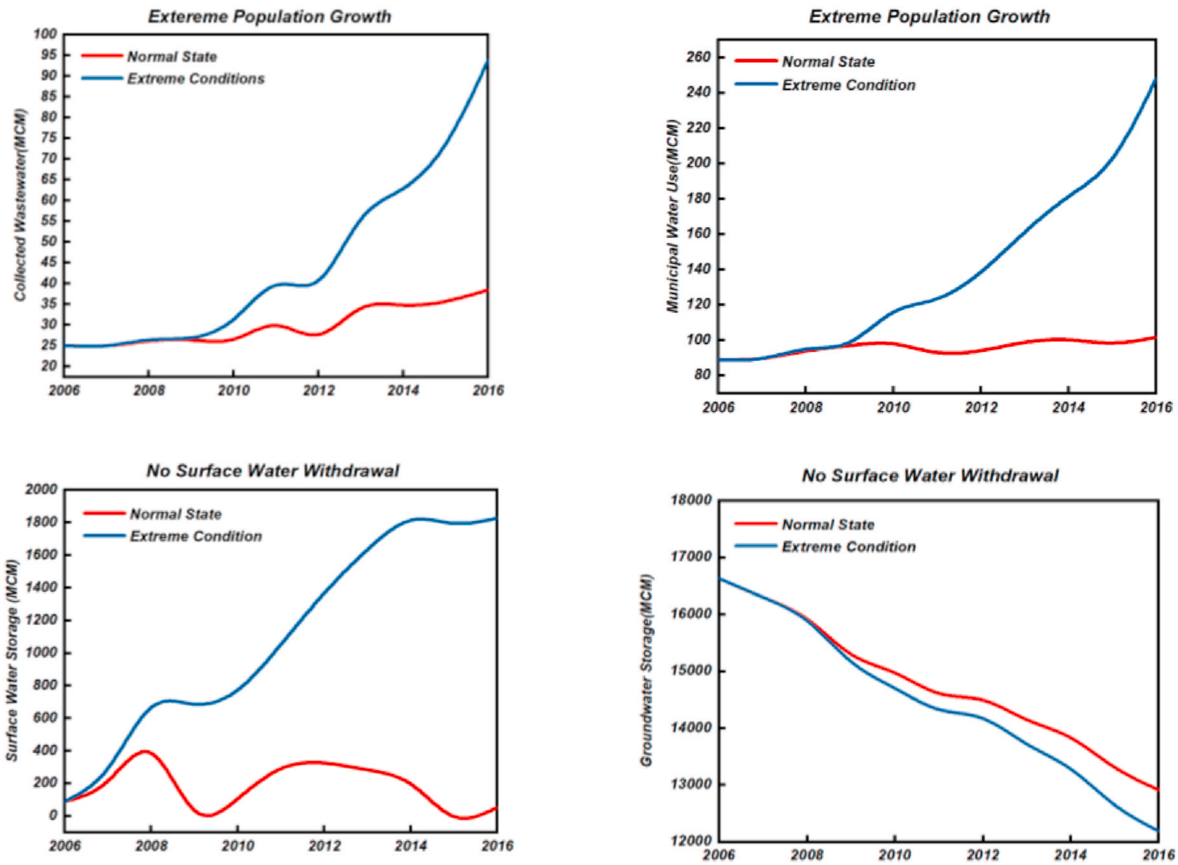

Fig. 8. The behavioral trends of selected parameters under extreme conditions.

storage declines. During both tests, only a set of certain variables were altered and other parameters were kept unchanged .

5. Policy scenarios

Different agricultural management, surface water management, energy consumption, and population growth policy scenarios were examined in this study using an annual time step. The policy scenarios, which are guided by policy scenarios considered for the central plateau of Iran (Gohari et al., 2013), include business as usual (B.a.U) and different combinations of surface water development, irrigation efficiency improvement, energy efficiency improvement, and population control (Table 2). B.a.U. assumes that municipal water demand increases due to population growth, and industrial water demands will not change during the simulation. Also, agricultural water demand will fluctuate slightly based on projected cultivated areas in the future.

Table 2
Policy scenarios.

Policy scenario	Description
Business as usual (B.a.U)	Surface water inflow from neighboring basins and inter-basin water transfer: 200 MCM same as long-term average; agriculture water use efficiency: 41.5%; population follows its long-term trend; groundwater withdrawal capacity: 1700 MCM; pump efficiency: 36%
Policy scenario I	Cropping change: alfalfa and barley are not cultivated. Other attributes are the same as B.a.U.
Policy scenario II	Irrigation efficiency improvement to reduce net agricultural water consumption: agriculture water use efficiency is increased to 61%. Other attributes are the same as B.a.U.
Policy scenario III	Surface water development: Nohob and Balakhanloo dams are built in the plain to control surface water and improve the irrigation networks; energy efficiency improvement: pump efficiency increases to 50%. Other attributes are the same as B.a.U.
Policy scenario IV	Surface water development: Nohob and Balakhanloo dams are built in the plain; Irrigation efficiency improvement: agriculture water use efficiency increases to 51%; population growth is decreased. Other attributes are the same as B.a.U.

6. System behavior indicators

Five system performance indicators were used to evaluate the potential effects of different management policies on each sub-system of the FEW Nexus in the Qazvin Plain. Four indicators, namely reliability, vulnerability, maximum deficit, integarated system performance index (ISPI), were selected to examine the long-term performance of the water resources system (Gohari et al., 2017). A fifth indicator, i.e. average energy intensity index, is defined as average energy consumption for withdrawing a unit volume of water (m^3) and used in this study to evaluate the amount of energy required for supplying each unit of water to stakeholders under different policy scenarios.

Hashimoto et al. (1982) defined reliability as the probability that water resources can satisfy various demands during the simulation period (Eq. (10)):

$$Reliability = \frac{Number\ of\ years\ with\ D^i = 0}{N} \tag{10}$$

In this equation, the numerator defines the total number of years with zero deficit for any consumer and N is the length of the simulation period.

The vulnerability index measures the severity of damage. It is defined as the average annual deficit divided by average annual demand for each water consumer (i.e., agricultural, municipal, and industrial) during the deficit period (Eq. (11)) (Sandoval-Solis et al., 2011):

$$Vulnerability = \frac{\sum_{j=1}^{N} D_j^i \Big/ Number\ of\ years\ with\ D^i > 0}{Water\ demand^i} \tag{11}$$

The maximum deficit index (Eq. (12)) represents the maximum annual deficit for each water consumer (Moy et al., 1986):

$$Maximum\ deficit = \frac{max\left(D^{i}_{Annual}\right)}{Water\ demand^i} \tag{12}$$

ISPI (Sandoval-Solis et al., 2011; Gohari et al., 2017) aggregates the above indicators as was calculated as follows:

$$ISPI^i = \sqrt[3]{Rel^i \times \left(1 - V^i\right) \times \left(1 - Maximum\ Deficit^i\right)} \tag{13}$$

The average energy consumption for pumping water per unit volume (m^3) was calculated to quantify the energy implication of water supply under different management scenarios. The wells was assumed to be static, including 3835 agricultural wells, 390 municipal wells, and 372 industrial wells based on the latest survey of groundwater wells (IWRMO 2013).

$$Average\ Energy\ Intensity = \frac{\sum_{i=1}^{n} Energy\ Consumption_i}{\sum_{i=1}^{n} GW\ Withdrawn\ Water_i} \tag{14}$$

7. Results and discussion

In business as usual (B.a.U) policy scenario, the regional water shortage severely increases as a result of growing water demands over the simulation period. Due to the increase in agricultural water demand, supplying more water to this sector exacerbates groundwater depletion over time. Fig. 9 and 10 show the trends of the selected variables throughout the simulation horizon (2020–2039) for different policy scenarios compared to the B.a.U scenario.

The B.a.U. Scenario is unsustainable, leading to great groundwater table decline and energy consumption. Continuous groundwater table drawdown causes energy consumption for groundwater pumping to increase from 1190 GWh to approximately 1400 GWh in the next two decades (Fig. 10). Consumed energy in municipal and industrial water sectors is insignificant compared to the intense energy usage in the agricultural sector, but due to lower groundwater table in municipal and industrial areas, withdrawing groundwater for these sectors requires more energy per unit of water compared to agricultural groundwater withdrawal. Under Policy Scenario I, reducing cultivated lands leads to reliable water supply during the simulation period, except for a 5-year period in the middle of the simulation when projected agricultural water demand exceeds water supply. Under this scenario, the trend of the groundwater table decline is less steep than the B.a.U scenario. Accordingly, average annual energy consumption is about 300 GWh smaller in comparison to the B.a.U scenario.

As shown in Fig. 10, energy consumption in the municipal and industrial sectors is small, similar to the B.a.U scenario. Effective water and energy conservation programs in the agricultural sub-system are critical policy leverages to reduce basin level water and energy demands. While reducing cultivated areas or changing crop patterns will not be a panacea, they can help reduce water and energy consumption

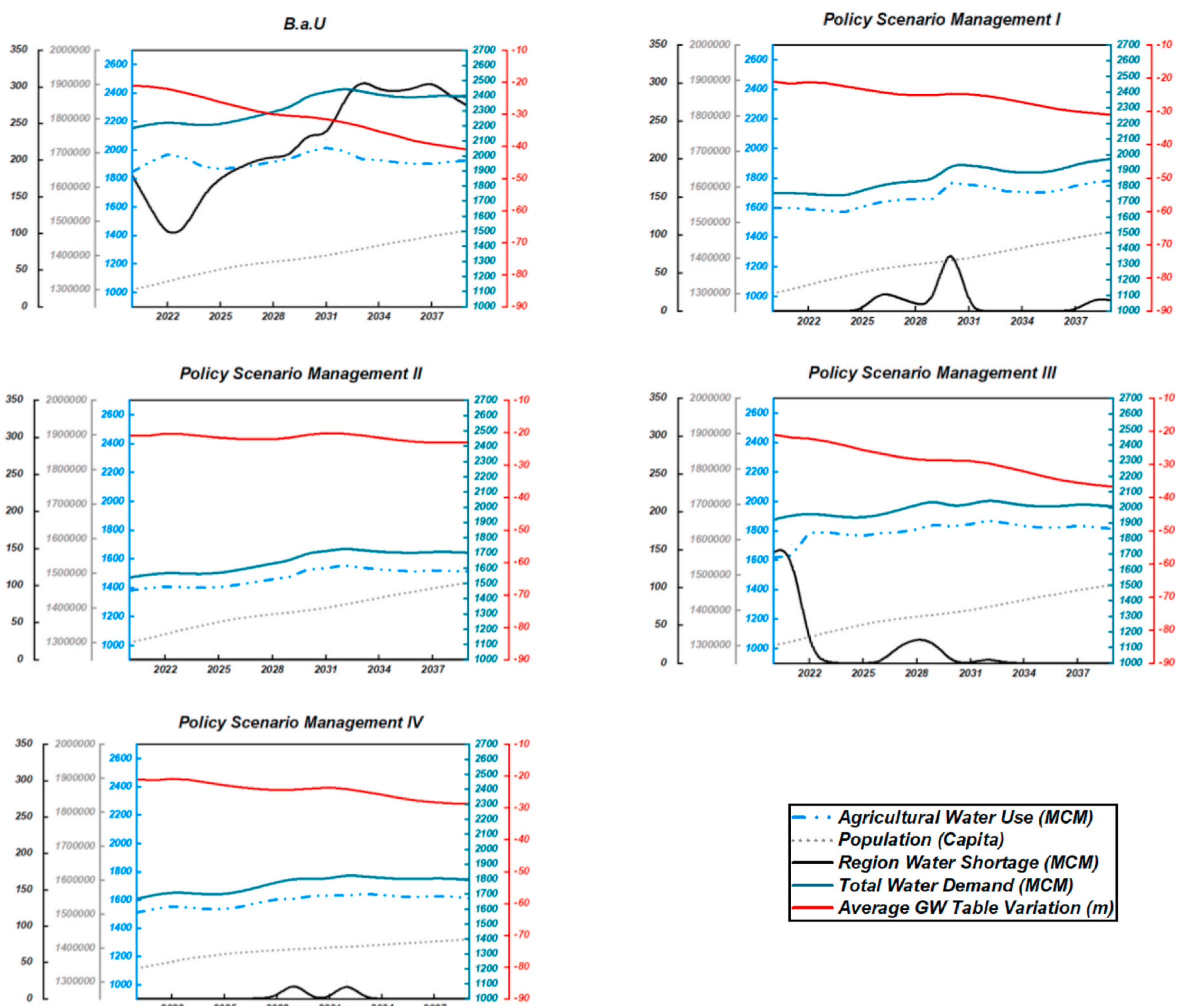

Fig. 9. The behavior of selected FEW nexus model variables under the simulated policy scenarios.

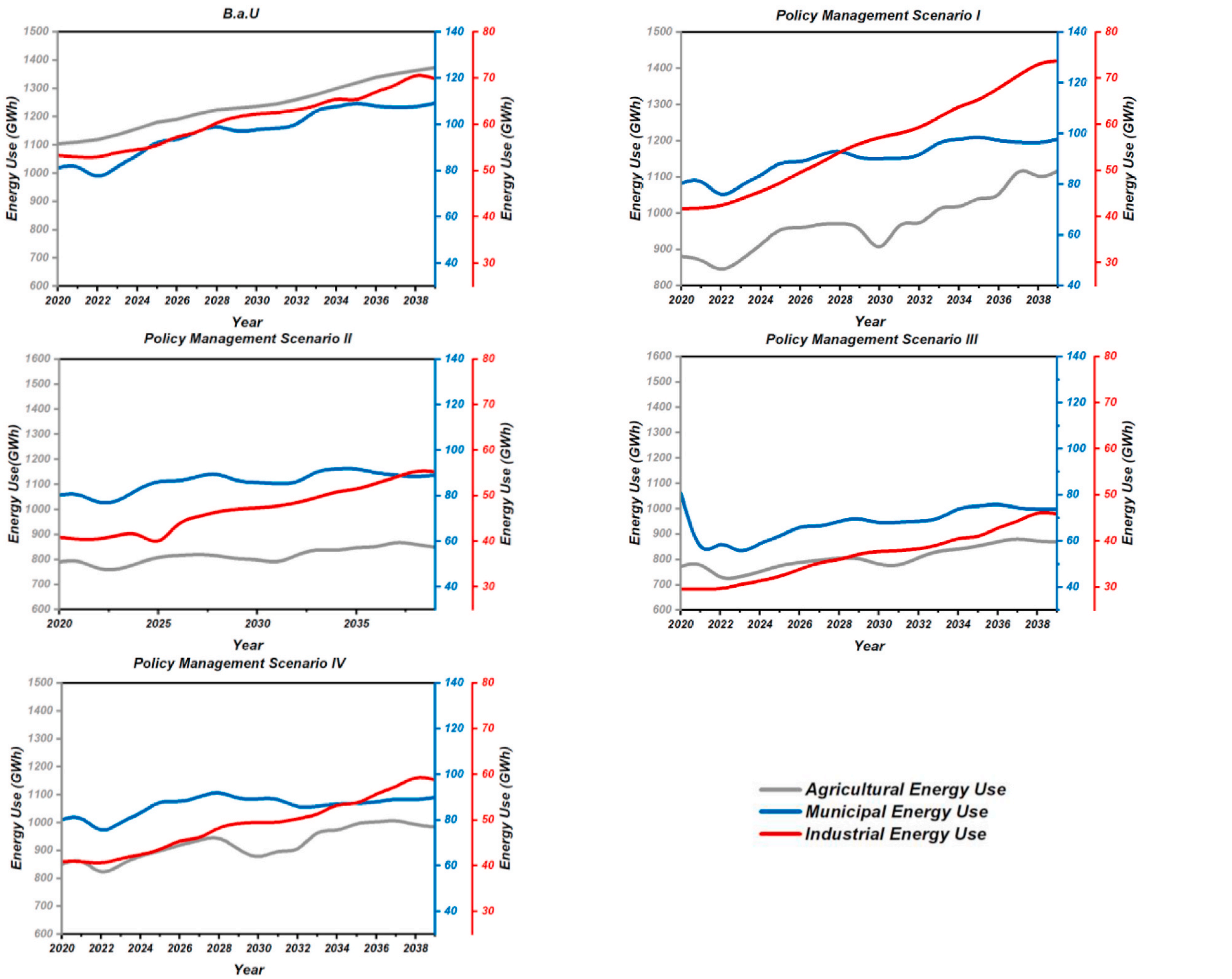

Fig. 10. Energy use in pumping groundwater in different sectors under simulated scenarios.

compared to B.a.U scenario. However, successful implementation of this policy requires rethinking of development and supporting policies to mitigate potential adverse impacts on agri-businesses. Energy consumption intensity for municipal/industrial and agricultural sectors can be estimated as 0.85 KWh/m^3 and 0.77 KWh/m^3, respectively, somewhat lower than the B.a.U scenario. Table 3 reports the results of various performance indicators under different scenarios.

Policy Scenario II results in less agricultural water use compared to the Policy Scenario I. Under this scenario, the system is able to meet sectoral demands without any water shortage throughout the simulation period. Energy intensity under Policy Scenario II is lower than B.a.U (Table 3) and energy use displays no significant fluctuation, ranging between 781 GWh and 970 GWh, due to the relative stability of the groundwater table. The total water demand in this scenario is considerably reduced in comparison to other policy scenarios, which leads to less groundwater withdrawal for supplying water to various stakeholders.

The results from Policy Scenario II underscore the key role of agricultural demand management to mitigate the decline of groundwater table over time. Because the population growth rate is constant like in previous scenarios, municipal and industrial water demands remain unchanged. As a result, less energy will be needed to withdraw water

Table 3
Reliability, vulnerability, maximum deficit, ISPI, and average energy consumption in pumping water of different stakeholders under determined FEW Nexus management scenarios.

	Municipal and Industrial					Agricultural				
Scenario	Rel	Vul	Maximum deficit	ISPI	Energy Intensity (KWh/m^3)	Rel	Vul	Maximum deficit	ISPI	Energy Intensity (KWh/m^3)
Business as usuall (B.a.U.)	1	0	0	1	0.87	0.00	0.100	0.13	0.00	0.80
Policy scenario I (No alfalfa and barley)	1	0	0	1	0.85	0.50	0.007	0.007	0.77	0.74
Policy management scenario II (Incrising irrigation efficiency to reduce net agricultural water consumption)	1	0	0	1	0.77	1.00	0.000	0.000	1.00	0.71
Policy scenario III (Building dams, increasing pump efficiency)	1	0	0	1	0.61	0.65	0.031	0.087	0.83	0.57
Policy scenario IV (Increasing irrigation efficiency, population control, building dams)	1	0	0	1	0.80	0.85	0.010	0.015	0.93	0.73

from the aquifer due to higher groundwater table in operational wells. The energy used to pump water for municipal and industrial sectors varies between 78 GWh and 91 GWh under scenario II. Overall, this policy package leads to minimum vulnerability and maximum reliability during the simulation period (Table 3). This policy is currently being implemented in some parts of the Qazvin Plain, although agricultural lands under high–tech irrigation systems are only a small fraction of total agricultural area in the plain. Farmers are given long-term loans to set up new efficient irrigation systems such as lateral move, drip and sprinkler. An essential prerequisite for successful outcome based on this policy is to ensure that groundwater savings will not trigger an expansion of irrigated agricultural lands, avoiding the rebound effect or Jevons' Paradox in increasing irrigation efficiency to mitigate agricultural water scarcity (Sears et al., 2018). To address this concern, the program requires installation of electric meters on electric-powered wells in lands under high–tech irrigation systems. Scaling up this policy to cover the entire plain is contingent on availability of significant financial resources and integrated water and land management.

While building two more dams (Policy Scenario III) alleviates the total water shortage in the plain compared to the B.a.U. scenario, it cannot eliminate water stress in the agricultural sector (Table 3). By regulating surface water, Nohob and Balakhanlou dams help reduce energy intensity of water supply in all sectors through smaller groundwater withdrawal and improved pump efficiency. On average, the energy required to lift groundwater for municipal/industrial and agricultural usages are about 0.8 KWh/m^3 and 0.73 KWh/m^3, respectively. Although increasing pump efficiency has a remarkable impact on energy use and profitability of the agricultural production, it is not effective in terms of water conservation because it does not reduce water demand. The system performance results of this policy are comparable to Policy Scenario II. This indicates that increasing irrigation efficiency aimed at reducing net water consumption in the agricultural sector can be an alternative to new surface water development, provided that appropriate land management policies can be adopted to prevent irrigating new agricultural lands using the saved waters.

In Policy Scenario IV produces similar results as Policy Scenario III. Slight water shortage is projected mid-simulation (2028–2034) due to high amount of agricultural water use. Potential effects of population control was also examined as part of Policy Scenario IV. Iran has achieved notable success in implementing family planning programs, which slowed down the rapid population growth after the 1979 Revolution (Danaei et al., 2019). Municipal water demand declined due to the decrease in population, which, in turn, reduced the volume of wastewater produced in the region. This resulted in a gradual recovery of groundwater table with an annual average of 0.4 m, stabilizing the energy use for water supply during 2020–2039. Under Policy Scenario IV, the amount of energy for water supply for agricultural, municipal, and industrial uses varies between 824 and 1002 GWh, 75 to 92 GWh, and 41 to 59 GWh, respectively. If population remained unchanged from 2028 to the end of the simulation period, the amount of energy used for wastewater treatment would be reduced by about 200,000 KWh/year.

This model-based analysis suggests that Policy Scenarios II and IV provide promising results for delaying the problem of groundwater depletion to sustain agricultural producution as an important economic activity in the region. Although the agricultural sector can continue to withdraw sufficient groundwater by using inexpensive energy under B. a.U., this situation will not be sustainable in the long run due to the problem of water limits to growth. The continuous increase in the required energy to provide agricultural water resources is a sign of the emerging water-energy challenges facing irrigated agriculture (Fig. 10). The projected depletion of groundwater storage within the next three decades is expected to threaten the sustainability and economic viability of irrigated agriculture and food production under status quo. This situation possesses the essential characteristics of a limits to growth problem (Meadows et al., 1972), a governing system archetype in water-scarce regions that undergo development beyond the natural limits of renewable water availability (Mirchi et al., 2012; Bahaddin et al., 2018). FEW nexus based water and land management policies designed to produce net water savings in the agricultural sector combined with recycling and reuse of treated wastewater can delay the severe negative consequences of growing water scarcity.

8. Caveats

It is important to recognize the SD model's limitations to realistically interpret the results (Gohari et al., 2013; Madani, 2013)A number of simplifications were made in model development and application. This model application intentionally focused on water scarcity issues because of the nature of agricultural water management problems in this semi-arid agricultural region. We did not examine the implications of flooding issues and associated policy scenarios (e.g., aquifer recharge) to address this likely extreme event. The model does not account for unexpected changes in croplands due to variability of crop profitability or due to socio-economic ramifications of international sanctions and associated implications for the viability of irrigation modernization initiatives. Another limitation is related to the use of exogenous variables as opposed to building completely endogenous causal relationships, which is a formidable task in complex systems such as water management in an agricultural plain. For example, auxiliary variables in the population sub-system, including literacy rate, urbanization rate, and regional GDP are exogenous and they are not affected by other model components (Fig. S19 in SM). The model assumes water allocation priorities and characteristics of the water management system will not change as compared to current management schemes and existing plans. As such, energy intensity per cubic meter to pump and treat wastewater, industrial water demand, environmental water requirement, inter-basin inflow and surface water inflow from neighboring basins in the future were considered to be the same as in the past.

Future model applications can examine feedbacks between the agricultural sub-system and the energy and population sub-systems to evaluate the influence of variation in food production (i.e., abundance or shortage of food) and its economic impact on population growth of the plain and energy use for crop production. Further, household income can be considered as a significant driver of household energy use, water use and food consumption. Currently, lack of data about household food consumption and energy footprint of agricultural fields (e.g., fertilizers, seeds, machinery and labor) pose a barrier to conducting these analyses in the Qazvin Plain. Future applications can also concentrate on evaluating the impact of climate change on crop water consumption and energy footprint, and viability of water markets as an adaptation strategy to cope with declining groundwater resources.

9. Conclusions

This paper presented a system dynamics model of regional water resource availability to meet the water demands of urban, industrial, and agricultural sectors in the Qazvin Plain, Iran, using a FEW nexus approach. System dynamics modeling is a useful approach for conceptualization and quantitative analysis of the interconnected FEW subsystems. The model quantifies the energy implications of water supply with respect to changes of interlinked FEW variables under alternative management scenarios. The existing water resources challenges in the Qazvin Plain will be exacerbated in the near future, leading to higher energy use to provide reliable water supply for local stakeholders. The status quo water resources management, which places increasing pressure on limited groundwater, creates water sustainability challenges within the next three decades. The signs of groundwater depletion are expected to emerge as increasing agricultural energy consumption and continued groundwater table decline (1 m per year). This trend will create challenges for irrigated agriculture. Population growth will increase the energy demand for the conventional operation of wastewater treatment with the expansion of the sewage system. A combination of

water demand and supply management policies (e.g., agricultural water savings and recycling treated wastewater) can delay the problem of water limits to growth in the Qazvin Plain. In particular, water savings in the agricultural sector is a critical strategy with respect to enhancing regional water availability and energy-efficiency of water supply. Future advancements of the FEW model of the Qazvin Plain include improved representation of agricultural water management and demand and land use dynamics to evaluate the implications of producing high-value crops to increase farm profitability, as well as potential unintended consequences of increasing irrigation efficiency through agricultural expansion motivated by agricultural water savings.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.111843.

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