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Research papers

An operational sociohydrological model to understand the feedbacks between community sensitivity and environmental flows for an endorheic lake basin, lake Bakhtegan, Iran

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ABSTRACT

Over abstraction for agricultural production and droughts in the Bakhtegan basin in southwest Iran has led to decreased lake volumes and has even dried in some years. These problems have occurred in the basin as a result of neglecting the roles that humans have played in lake desiccation. This study developed a socio-hydrological model to understand such dynamic interactions between the economy and community's sensitivity to the environment in the period of 1999 to 2013. The WEAP model was used to simulate the hydrological system that is (bi-directionally) coupled to a society model simulating community sensitivity. A multi-objective optimization algorithm was used to estimate the parameters of the coupled model. The results of the model calibration and validation in estimating the simulated discharges show good performance of the model in simulating observed streamflows (R^2 and NSE ranging between 0.73 and 0.99 and 0.31 to 0.99 respectively), agriculture water supplied (R^2 and NSE ranging between 0.00 and 0.69 and −7.08 to 0.58 respectively), migration and population (R^2 and NSE for migration: 0.29 and 0.63). The results of the integrated model on community response showed that attention to environmental conditions, such as lake levels, was heightened right after the drought events of 2000–2001 and 2008–2010. The effect of the latter event was even accentuated by several human interventions such as operationalization of Sivand and Mollasadra dams and transfer of pristine lands to agriculture. This led to major contraction of the lake. The model interprets that heightened community sensitivity as a result led to public policy dialogue and change. Water was taken away from agriculture and given to the environment leading to temporary lake revival. This was also confirmed by reviewing government decisions in 2011, further validating the value of socio-hydrological models in interpreting feedbacks between community sensitivity and environmental flows.

1. Introduction

Humans have adversely affected water resources around the world as a result of increasing population, technological development and economic growth. In the era of the Anthropocene (Savenije et al., 2014; Sivapalan, 2015), humans are changing their environment and adapting themselves to those changes (Palmer & Smith, 2014). Human actions have a multitude of impacts on the hydrological dynamics at the scale of the catchments. Changes in land use, changes in crop patterns, construction of dams and hydraulic structures alter river flow regimes, overharvest groundwater resources and reduce recharge to groundwater (Hedayat et al., 2017), deteriorate of water quality due to pollution of water resources, as well as numerous other impacts on biogeochemical cycles and riverine and lake ecology (Montanari et al., 2013). Human awareness of sustained environment degradation can also lead to changes in the way water is managed (Elshafei et al., 2014; Van Emmerik et al, 2014). A future with sustainable water development can therefore be a consequence of feedbacks from past human actions and accurate forecasting of long-term environmental damage.

Recent evidence suggests that the relationship between humans and water resources is at such a level of complexity that humans should be considered as an active agent, capable of bringing change to its environment (Thompson et al., 2013). This has motivated several socio-hydrological models (Blair & Buytaert, 2016; Levy et al., 2016; Troy

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et al., 2015) that integrate hydrological and social processes by conceptualizing dynamic (one-way or two-way) feedbacks between society and its water environment (Montanari et al., 2013; Sivapalan et al., 2012).

Several socio-hydrological studies have highlighted that social processes are influenced by economic development (Kandasamy et al., 2014; Roobavannan et al., 2017b), which often depends on agricultural growth. Agriculture provides around 60% of all jobs in developing countries (Rieu-Clarke et al., 2015; Roobavannan et al., 2017a). On the other hand, agriculture is one of the most water consumptive economic sectors, relying on water to grow agricultural biomass. The excessive use and degradation of the quality of water resources makes it scarce. This scarcity effect also makes water economically more valuable in monetary terms and therefore may lead to conflicts between agriculture and the environment.

Not surprisingly, there is a rising concern that agricultural growth would lead to reduced delivery of environmental water and subsequent ecosystem degradation. (Mahabadi et al., 2018; Sajedipour et al., 2017; Tabouzadeh et al., 2016). However, human actions, such as the expansion of irrigated areas to increase economic benefits also lead to changes in social aspects, such as behavioral norms and social memory (Kinzig et al., 2013). Behavioral norms towards (and social memory of) past degradation events sensitizes communities to ongoing degradation (Elshafei et al., 2015). This, in turn, sensitizes societies about impending undesirable events. Social memory, therefore, is a fundamental mechanism that connects hydrological change to societal response (Gober & Wheater, 2015).

One of the areas affected by adverse human actions is the Bakhtegan Lake Basin (BLB) in southwest Iran. The Bakhtegan lake of the basin was dry in the summer of 2007 and has also been dry in recent years (Sajedipour et al., 2017). Only recently has the lake's extent recovered and stabilized after witnessing desiccation and interrupted recoveries in the early 2010s due to over-abstraction (Bakhtegan wetland's water intake up by 900% - Tehran Times, 2020). Construction of dams and over-appropriation of water for agricultural purposes as a result of the expansion of irrigation areas in upstream parts of the basin are the main causes of drying downstream of Bakhtegan Lake, which has been a valuable habitat for migratory birds (Mahabadi et al., 2018; Tabouzadeh et al., 2016; Rafii et al., 2011). The loss of forest cover around the lake, the dispersion of dust and salt particles from the dry bed of the lake, and the death of some animal species are adverse effects that follow the drying of the lake. This basin includes 46 species of mammals, 218 species of birds, 36 species of reptiles, and 23 species of fish that are valuable attraction for tourists and researchers. Loss of such biodiversity would be a terrible environmental tragedy and hence the dynamics of lake recovery deserves careful investigation (Tangestani et al., 2013).

"Pendulum swing" has been described by Kandasamy et al (2014) to show a turn-around from agricultural development and food production to the community-inspired reallocation of water back to the environment (Roobavannan et al., 2017a). The key underlying mechanism is community sensitivity and response mediated competition for water between agriculture and the environment. The phenomenon has been observed and modeled in several basins. Kandasamy et al. (2014) demonstrated the emergence of the phenomenon in Murrumbidgee River Basin in eastern Australia, where the degradation of wetlands at the downstream end led to decreased water use in irrigated areas so that more water could be released for improving environmental health. Toolbin Lake Basin in Western Australia (Elshafei et al., 2014; 2015), the Tarim River Basin in western China (Liu et al., 2014) and the Kissimmee River Basin in Florida in the United States (Chen et al., 2016) are other basins where a pendulum swing has been reported and interpreted through data analysis and socihydrological modeling.

This study aims to investigate the phenomenon in the BLB and understand the possible influence of community response to *partially* recover and stabilize the lake in the early 2010s. The intention is not to investigate whether the pendulum swing (which implies sustained environmental development) occurred in the basin. Instead the paper investigates how community responds to economic growth and environmental degradation and delivers improved ecosystem services under good economic conditions. For the first time, a detailed conceptual hydrological model is embedded within the sociohydrological model of Roobavannan et al. (2018) and operationalized in order to better understand the dessication and recovery, even though *temporary*, of an endorheic lake and the role that community sensitivity played in shaping societal response to that effect. Few previous studies have investigated the dynamic feedbacks between the community and its environment in the basin, e.g. in terms of social learning (Benhangi et al., 2017; 2018; 2020). Although Mahabadi et al. (2018) provided a social-ecological system model to understand the economic impacts of climate change in the basin, this paper evaluates the co-evolution of societal response with changing economic growth and environmental degradation for the first time. This study therefore serves as a modeling template for more realistic socio-hydrological predictions and efficient water management that endogenizes human values and norms (Roobavannan et al., 2017a; 2018).

2. Data and methods

2.1. Study area

BLB is an endorheic basin located in southwest Iran. The Kor and Sivand Rivers are the major rivers in the basin. The Kor River is the longest and most important river that caters to agriculture water demands in the basin. Also, this river supplies drinking water to cities within Marvdasht and Shiraz provinces. The Bakhtegan and Tashk Lakes are located at the downstream end of the basin and are recognized as important places for breeding birds (Important Bird Area, IBA) by Bird Life International (Sajedipour et al., 2017). The area of Bahtegan Lake is about 750 km^2, approximately 77 km in length, about 10 km in average width, and it is also the second largest lake in Iran. During the wet seasons, the maximum depth of the lake is 3 m and the average depth of the lake is between 0.3 and 0.5 m. River discharge at the junction of Kor and Sivand rivers have decreased in the last decade due to the rising demand for agricultural water that led to drying lakes (Sajedipour et al., 2017).

Benhangi et al. (2018; in Persian) provide a comprehensive overview of the major anthropogenic pressures that have profoundly altered the BLB over time (see Fig. 1). In particular, some key events are discussed here. The "Agricultural expansion in the agricultural growth poles" law was legislated in 1975 that led to increased irrigation area in Marvdasht city, located in the BLB. In order to make Marvdasht the largest agricultural pole in Fars province, the Dorrodzan Dam and irrigation pumping systems were built around the same time.

More than 200 thousand hectares of national lands were transferred to applicants by the government as a result, which led to significant increase in the area under cultivation and, subsequently, led to increased pressure on the province's water resources. During the time that the government transferred the lands, other areas were illegally seized by the farmers. By the end of 2005, more than 35 thousand hectares were unauthorized acquisitions (Benhangi et al., 2018). About five thousand of those unauthorized acquisition lands were legally transferred to farmers in 2006 (Benhangi et al., 2018). In order to cater to such an increase in agricultural demand, the Mollasadra Dam with a capacity of 411 MCM was constructed and operationalized in 2007 and the Sivand Dam with a capacity of 142 MCM was operationalized in 2009 on the rivers feeding the lake (Kor and Sivand rivers respectively, see Figs. 2 and 4). A large part of Lake Bakhtegan had dried up in August 2007 and as a result 2,000 Flamingo chicks that had not yet been able to fly had died in its dry, salty bed. The extent of Bakhtegan Lake was significantly lower in the following two years (Bagheri et al., 2016). Towards 2011, excessive water withdrawals from illegal wells and over-appropriation of water resources for expanded agriculture caused evident

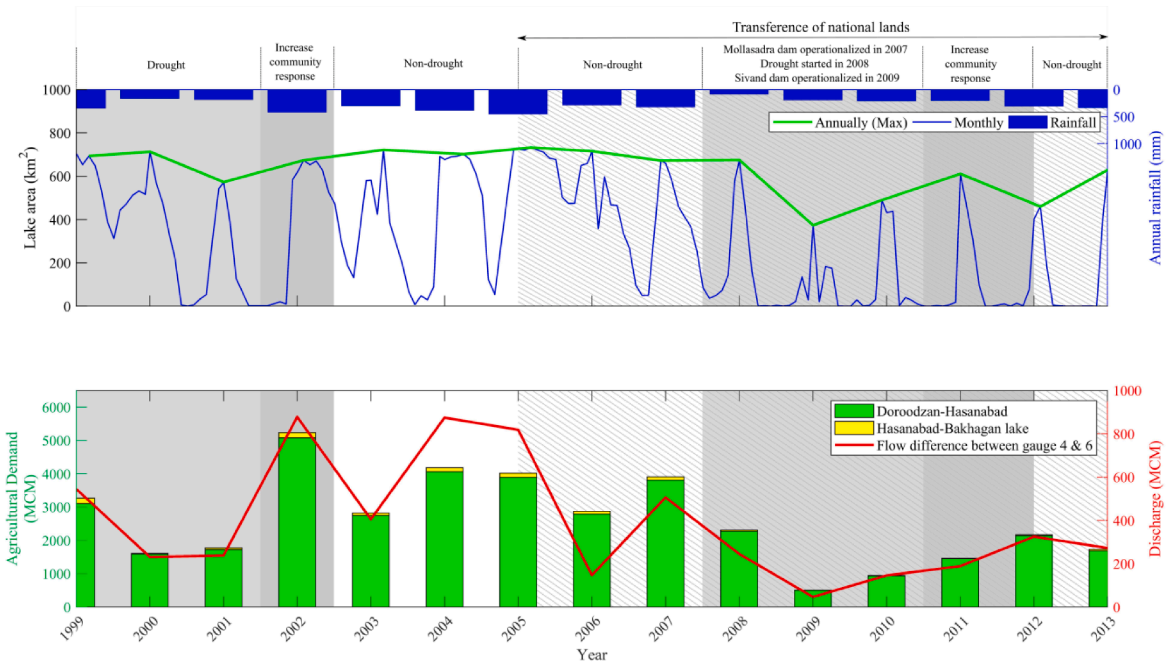

Fig. 1. a) Bakhtegan lake area processed in GEE (Google Earth Engine) using high-resolution Landsat 5, 7 and 8 images, and annual rainfall (source: see Table 1), b) agricultural demands of Doroodzan-Hasanabad and Hasanabad-Bakhtegan Lake regions, and flow difference between gauge 4 and 6 that contributes to agricultural demands of the two regions. First drought start in 1999 and lasts till mid- 2001, while the second drought occurs in 2008. In the first drought the lake level recovery coincided with the recovery of the lake. The lake recovery around the second drought period happened during the drought with lower than normal water being allocated to agriculture to the downstream agriculture demand centers, the Doroodzan-Hasanabad region and near zero water allocated to the agriculture in Hasanabad-Bakhtegan Lake region. This is indicated by the flow difference from 2009 to 2012.

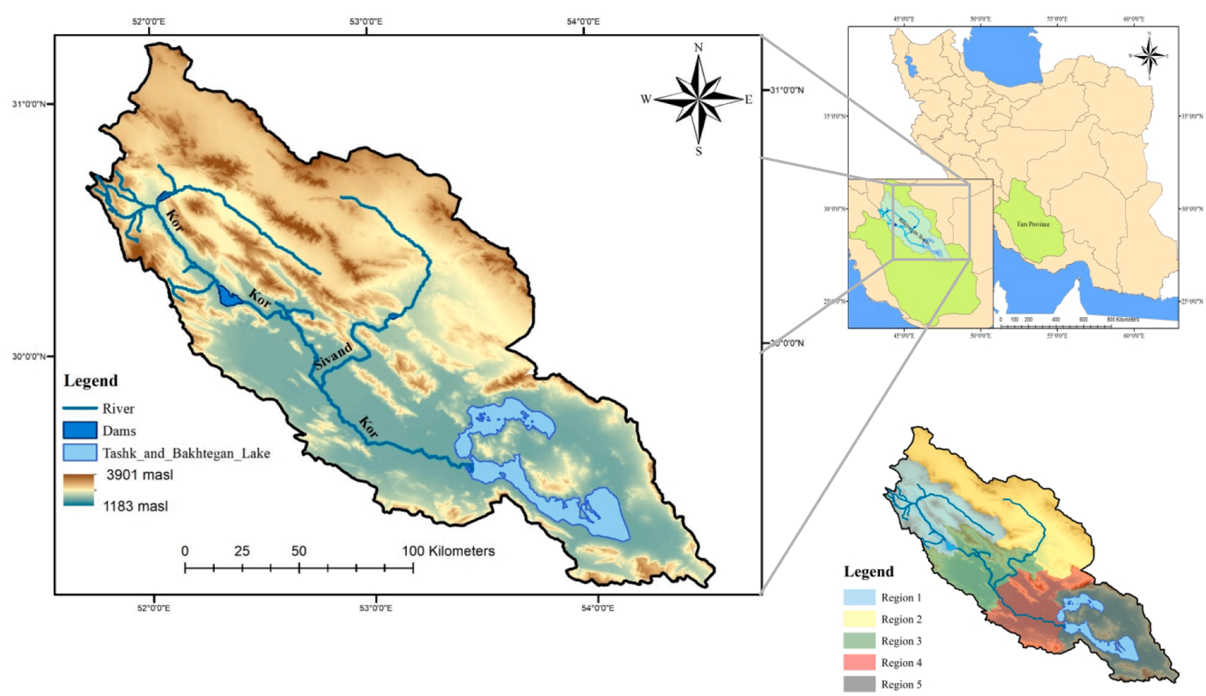

Fig. 2. The location of Bakhtegan Lake Basin (BLB). Also shown are various regions of the basin as described in the text.

environmental degradation, including a reduction in the extent of the Bakhtegan lake and thus endangering plant and animal species (Rafiee et al., 2010). This led to communal agitation in response to which the Environmental Protection Agency and the Ministry of Energy of Iran took necessary measures to curb violators and increase environmental flows in 2011 (Nasim news, 2012). Also, below we present two examples of local representatives requesting the President to force his cabinet to supply the environmental demand of Bakhtegan lake (Nasim news, 2012; Tasnimnews, 2013). These we believe must have emerged from intense dialogues between local population and their representatives to the extent that the representatives felt obliged to formally request the national government for a change in water management practices. The

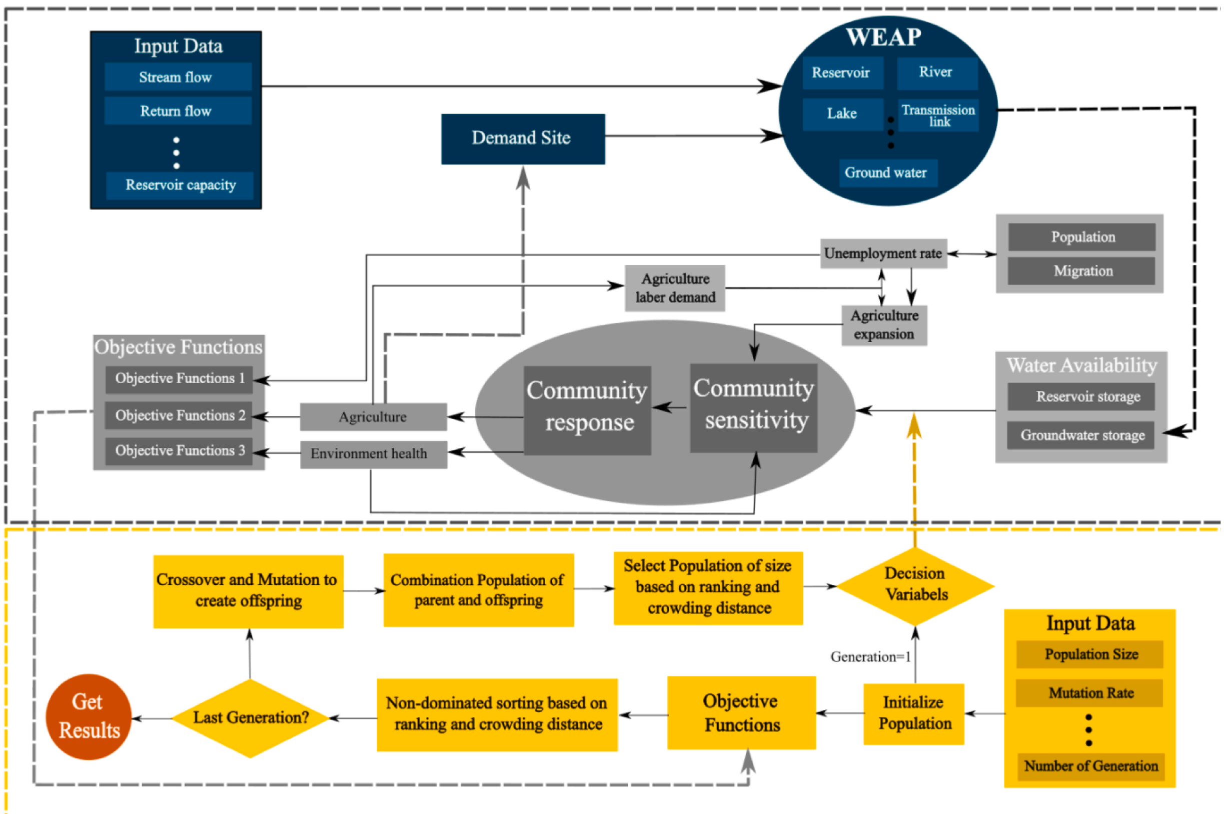

Fig. 3. The coupled model conceptualization used to study the sociohydrological dynamics of Bakhtegan Lake Basin.

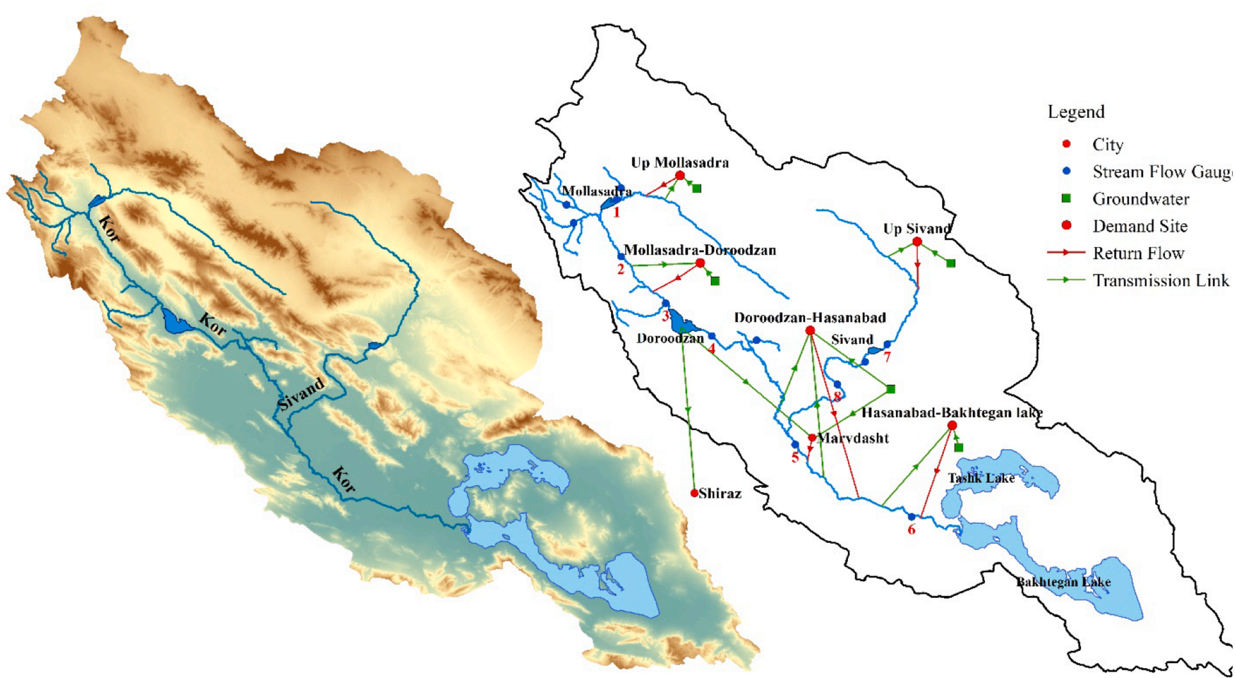

Fig. 4. WEAP model schematic for the Bakhtegan Lake Basin (BLB).

Ministry of Energy, also responsible for supplying environmental flows, released Bakhtegan Lake's demand for environmental flows from Dorrodzan Dam as a result in 2011 (Fig. 5).

2.2. Sub basins of BLB

BLB is subdivided into five regions (see Fig. 2) based on societal development processes and hydrological and hydrogeological boundaries (Benhangi et al, 2017; in Persian).

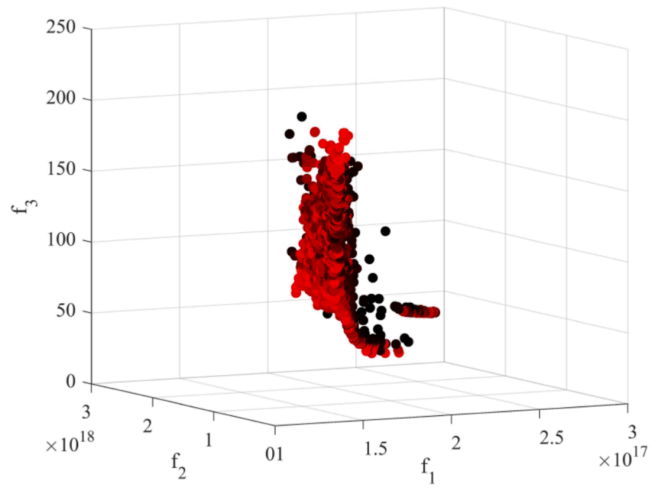

Fig. 5. Pareto front in red, containing non-dominated parameter sets, obtained from multi-objective optimization (by NSGA-II) after 15,000 coupled model simulations. Dominated parameter sets are shown in black. f_1, and f_2, are sums of squared differences between observed discharge and discharge estimated by the coupled model at gauge numbers 4 (linked to agriculture demand) and 6 (linked to environmental demand; see Fig. 3) respectively. The third objective f_3 is the sum of squared difference between observed and predicted unemployment rate in BLB. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Region 1: Upstream of Mollasadra Dam (Up Mollasadra) is a region where farming lands are divided into smaller areas, especially orchards in upstream areas and rice in downstream areas. Building Mollasadra Dam has led farmers to expand farming lands by using dam storage via pumping. Increased withdrawals in upstream areas has also led to excessive use of groundwater in this region.

Region 2: The area upstream of Sivand Dam (Up Sivand) is mountainous and has limited water resources. Similar to Up Mollasadra, water consumption is higher in upstream areas than downstream, where farmers use modern irrigation systems for orchards.

Region 3: The Mollsadra-Doroodzan region is located between Dorrodzan Dam and Pole Khan. Agriculture expansion in this region was facilitated by the Dorrodzan Dam and government policies upstream. In order to sustain agricultural profits during droughts, the farmers in this region have switched to groundwater instead of decreasing irrigation area. As a result, the groundwater level declined and became unusable, leading farmers to grow almond, olives, and saffron. The expansion of irrigation networks further increased water scarcity in the region because additional availability of water led to further increase in the farming area from 46 thousand hectares to 72 thousand hectares.

Region 4: The Doroodzan-Hasanabad area from Pole Khan to Bakhtegan Lake has witnessed most of the adverse impacts of activities in upstream regions (Region 1–3). Unofficial institutions coordinate farmers to deal with these impacts by changing cropping patterns and irrigation systems. Groundwater, being saline due to over extraction, is unusable for farming. As a result, many of the farmers changed their occupation or emigrated to other areas for farming. Desolated rural areas shows the aftermath of migration in this region.

Region 5: The Hasanabad-Bakhtegan Lake area has been used for dry farming. The pattern of community behavior in this area is similar to Doroodzan-Hasanabad area. Rainfed figs have been planted in most of the region.

2.3. Model set up and parameterization

Following Roobavannan et al. (2018), the presented socio-hydrological model (Fig. 3) dynamically couples the basin's hydrology with a "Society" model. The model is linked to an optimization scheme to calibrate the parameters of the model. The model couples a water demand and balance-based WEAP (Water Evaluation And Planning) model with community sensitivity equations of the model by Roobavannan et al. (2017b). The advantages of using the WEAP model rather than the water mass balance in the Roobavannan et al. (2017b) are that the entire basin is more realistically modeled, utilizing available observations to a fuller extent and considering both surface and groundwater resources. The Elitist Non-Dominated Sorting Genetic (NSGA-II) Algorithm (Deb et al., 2002) is used to calibrate the coupled model parameters based on observed annual streamflow at two gauges and unemployment statistics within the basin.

The presented sociohydrological model is a coupled water-society model. WEAP is the water system model that estimates available water in the basin. This is an input to the society model at each simulation time step. In the society model, the community sensitivity, which is a function of economic conditions of the society and the state of the environment, influences community response to allocate water for agricultural and environmental needs. The amount of agricultural water allocation determines the unemployment rate based on how many are employed in the agriculture sector that is limited by agriculture water availability. Outmigration is interpreted and modeled as a function of agriculture unemployment and partially influences the population of the basin in the next simulation period. This population is used to calculate the need for drinking water as well as the unemployment rate for the next time step. The agricultural expansion, reflecting the limitations of water and land resources and labor in each period, has a two-way relationship with the unemployment rate, and has a direct impact on the community response. This is in addition to the impact of community sensitivity on community response, which when exceeds a certain threshold leads to a change in allocation of water between agriculture and the environment.

2.3.1. Hydrological model (WEAP)

WEAP is semi-theoretical, semi-distributed, and deterministic model (Abrishamchi et al., 2007). It integrates water balance components (such as evapotranspiration, runoff, baseflow, etc.) with man-made interventions (such as dams) through watershed-scale hydrologic processes and can be used in urban or agricultural hydrological systems. WEAP has been used to evaluate water allocation and management across a range of climatic, hydrological and socio-economic conditions (e.g. Bhave et al., 2020; Karlberg et al., 2015; Mehta et al., 2013). In this case study (Fig. 4), the components of WEAP that have been implemented at an annual scale consist of: 1) rivers (two main rivers), 2) reservoirs (three dams), 3) demand sites (drinking water and agriculture demands), 4) groundwater, 5) transmission links, 6) return flows and 7) environmental flow requirements. Fig. 3 shows that water storage is calculated by WEAP and used as an input to the society model. Evapotranspiration, runoff, infiltration and irrigation supply are five key processes modeled in WEAP based on the decision context, stakeholders' requirements and balancing model complexity with data availability (Sieber, 1990). Using WEAP as the water system model, the socio-hydrological model has the ability to consider different scenarios of, e.g., climate and crop patterns. The model was calibrated based on past observed climate and cropping patterns in the basin. Nonetheless it would be useful for future research to investigate different climate change scenarios and changes in crop patterns as inputs in the socio-hydrological model for forecasting future conditions and how communities respond to it.

Irrigation demands were calculated by Ghafarijoo et al. (2016, In Persian) for each region in BLB based on the cropping pattern and crop water demands. Data from Ghafarijoo et al. (2016, In Persian), such as of Kor and Sivand rivers headflows, the reservoirs net evaporation '(evaporation minus precipitation on the reservoirs' surface), observed reservoir volumes and streamflow data, are used to develop the WEAP model for BLB. The model does not include return flow to recharge the groundwater but return flows to the rivers are considered.

According to the available information, total consumption (excluding the Doroodzan Dam outlet) in the catchment areas of Tashk Bakhtegan and Maharloo Lakes is 5.51 billion cubic meters (excluding 0.29 billion cubic meters of sewage from springs and aqueducts without or without consumption, (40-year long-term water balance, 1967–2007)). It is estimated that 27.59 percent of this consumption is uncertain (1.52 billion cubic meters of surface water is supplied). Total groundwater consumption (wells and aqueducts) is 3.99 billion cubic meters and about 72.41 percent of the total catchment area (Groundwater resources, Report of Jamab Consulting Engineers Company, 2013). Based on WEAP's ability to consider the withdrawal ratio of surface and groundwater in BLB, we assumed that groundwater would supply 75 percent of demand. Furthermore, the first priority of withdrawal from groundwater resources, as shown in Fig. 3 (transmission links), has been considered.

Reservoirs' water mass balance equations are presented in the following Table 1:

2.3.2. Society model

2.3.2.1. Population and Migration. Births (B), deaths (D) and economic migration (M) are factors that determine changes in population. A change in population (P) is calculated by:

$$\frac{\dot{P}}{P} = B - D + M \tag{1}$$

where $\dot{P} = \frac{dP}{dT}$ and birth and death rates and economic migration are fluxes at an annual scale (number/year).

Migration is assumed to be solely linked with the economy even though migration could also be induced by climate change, politics or other issues.

Following Roobavannan et al. (2017b) and Lyu et al. (2019), who have found migration to be a function of the unemployment gradient in the Murrumbidgee river basin in Australia and Jiangsu province, China. Given that the unemployment rate is one of the most important migration factors in Iran (Esfandiari and Nabieian, 2018; Ghader, 2018), migration is assumed to be proportional to the difference between unemployment rates in the basin and the rest of Iran.

$$M = \upsilon(U_I - U_B) \tag{2}$$

where U_I is the unemployment rate of Iran, U_B is the unemployment rate in the BLB and υ is a constant.

The unemployment rate is determined by:

Table 1
Reservoir water balance variables and equations ((Dehghanipour et al., 2019).

Parameter	Definition	Unit	Equation/data source
ΔS	Storage change	L^3/T	$\frac{\Delta S}{\Delta t} = Q_{in} - R - (E_v - P)A - S_p$
S	Storage	L^3/T	Ministry of Energy of Iran (2016)
Q_{in}	Upstream inflow	L^3/T	Ministry of Energy of Iran (2016)
R	Release	L^3/T	Relate to demands in downstream(Social model)
P	Precipitation rate	L/T	Ministry of Energy of Iran (2016)
E_v	Evaporation rate	L/T	Ministry of Energy of Iran (2016)
A	Reservoir surface area	L^2	Function of storage
S_p	Spillway	L^3/T	$S_p = \begin{cases} 0 & S \leqslant S_c \\ \alpha(S - S_C)^{1.5} & S \leqslant S_c \end{cases}$ $\alpha =$ *overflow parameter*
S_c	Storage Capacity	L^3	Ministry of Energy of Iran
Q_T	Drinking water	L^3	$Q_T = w_P P$

$$U_B = Max(0, \frac{P\varphi - D_a}{P\varphi}.100) \tag{3}$$

where φ is the labor participation rate of the population and D_a is the labor demand of the agriculture sector. This equation assumes that agriculture dominates the basin's economy (Ghafarijoo et al., 2016).

Following efficiency conditions provided by Roobavannan et al. (2017a; b), change in labor demand in agriculture is assumed to depend on the change in the irrigated area ($\frac{\dot{L}_a}{L_a}$) which is contingent on water irrigation supply, the growth rate of the total factor of productivity (TFP) in agriculture (γ_a), the wage growth rate (γ_W) and the productivity share of land in agricultural output (α).

$$\frac{\dot{D}_a}{D_a} = \frac{\dot{L}_a}{L_a} + \frac{\gamma_a}{\alpha} - \frac{\gamma_W}{\alpha} \tag{4}$$

On the other hand, population size determines the drinking water demand, as shown in Table 1. where w_P is domestic water use per capita.

2.3.2.2. Ecosystem services (Es). Ecosystem services are defined as the conditions and processes by which natural ecosystems and its inhabiting species sustain and fulfill human life (Daily,1997). The delivery of ecosystem services, E_S, as part of the Society model, affects community sensitivity towards environmental health and degradation. It is calculated by a seven-year moving average of the Fish Species Richness (FSR) index (Yoshikawa et al., 2014) given by:

$$E_S = \beta_0 Q_B^{\beta_1} \tag{5}$$

where Q_B is the observed discharge into the Bakhtegan Lake (Fig. 4),β_0 and β_1 are parameters with values obtained from Yoshikawa et al.(2014)

2.3.2.3. Community sensitivity. It is expected that wide participation is required to bring about a change in social behavior and change in associated water use and management (MDBA, 2017). Community sensitivity plays a vital role in that regard. Elshafei et al. (2014) proposed an equation based on vulnerability and resilience theories (Roobavannan et al., 2017a) and conceptualized community sensitivity by comparing economic conditions with delivery of ecosystem services. Although society is heterogeneous in terms of income, education and politics which all impact its collective behavior and action (Magnani, 2001), the community is assumed to be homogenous in BLB. This community is similar in terms of religion and the main occupation of agriculture, rural areas in most areas, and so on. Although we assumed that the community is homogeneous, we used the WEAP model to consider the five different areas in the Bakhtegan Basin to incorporate agrohydrological heterogeneities so that the results are of the required quality.

$$\dot{V} = \gamma_V[(-\widetilde{E}_S - \widetilde{I}_C)]V \tag{6}$$

where $\dot{V} = \frac{dV}{dt}$ is community sensitivity's change, γ_V is a timescale parameter determined by social, economic and political factors (Elshafei et al., 2014; Roobavannan et al., 2017a),$\widetilde{E}_S$ is the change in the delivery of ecosystem services of the basin and $\widetilde{I}_C$ is the change in income per capita for the population in the basin, given by:

$$\widetilde{E}_S = \frac{\Delta E_S}{\overline{E}_S} \ , \widetilde{I}_C = \frac{\Delta I_C}{\overline{I}_C} \tag{7}$$

where $\overline{E}_S$ is the average ecosystem services over the past five years and $\overline{I}_C$ is the average income per capita over past five years (Roobavannan et al., 2017a).

2.3.2.4. Community response. According to the concept of community response, presented by Roobavannan et al. (2017a), a community that is highly sensitive to environmental degradation, is further sensitized by adverse environmental conditions. Such heightened sentiments override the inducement for agricultural expansion (De), trigger management actions to divert water away from agriculture and reallocate it to the environment. This trigger is modeled through a response function X. Water reallocation to the environment occurs when X is positive and exceeds a certain critical sensitivity threshold Vc*. During the simulation period, the community response is therefore updated every year as a function, as conceptualized by Roobavannan et al. (2017a). To exemplify this further, excessive drying of lakes over time can lead to sensitivity heightened beyond a tolerable threshold, resulting in responses to increase environmental flows to the lakes. The response function (X) shown below determines the change in community behavior and their response to an increasingly degrading environment, resulting in more water being released to the Baktegan Lake. Community sensitivity depends on the social and environmental values of the community, local actions, lobbies, and the like. As a result, a change in the environment leads to a change in community sensitivity that eventually leads to a shift in water management behavior and decisions (Elshafei et al., 2014; see equation (6)). The allocation of water and the release of more environmental flows are examples of actions resulting from increased community sensitivity that affects the feed backs to the economy through, e.g. reduced water for agriculture, lower agricultural production and higher agriculture unemployment (Roobavannan et al., 2017a).

$$X = \begin{cases} -K_d D_e & F(V) < V_C^* \\ F(V) - K_d D_e & F(V) \geqslant V_C^* \end{cases} \quad (8)$$

where K_d is a scaling factor, D_e is inducement for agricultural expansion, V_C^* is the critical community sensitivity and *F(V)* is normalized sensitivity given by:

$$F(V) = \frac{\dot{V}}{V_m - V} \quad (9)$$

where V_m is an arbitrary constant reflecting the maximum sensitivity of the particular community (Elshafei et al., 2014).

Kindly note from Equations (6), 8 and 9 that a change in community sensitivity is proportional to a change in community response – hence the model assumes no lag between the two. Community sensitivity and community response are filtered processes, which depend on the past sensitivities and responses with certain lags (as encapsulated by γ in equation (6) for example). Nonetheless there should be some slight delay between the two that depends on the characteristics of the community and the temporal scale of the analysis.

The inducement of agricultural expansion, D_e, exhibits society's incentive to grow using land to increase production.

$$D_e = \left[\frac{\dot{P}}{P} + U_B\right]\left(1 - \frac{L_a}{L_m}\right)\left(1 - \frac{R_e}{S_c}\right) \quad (10)$$

Available labor is influenced by population growth and the unemployment rate. Additional water and farming land available are other restrictions on agricultural expansion. R_e is the total predicted water supply that may be extracted, for instance, for irrigation and town water supply. S_c includes all water resources that can be utilized for expansion. L_a is the irrigated land area, L_m is the maximum land available for agriculture and the corresponding factor, $\left(1 - \frac{L_a}{L_m}\right)$, indicates fraction of land available for further expansion.

The response function affects water management and changes allocation between agriculture and the environment. Roobavannan et al. (2017b) suggested an equation based on Elshafei et al. (2014) on how water allocation for agriculture may change when X changes sign:

$$\dot{Q}_A = \begin{cases} \eta_E \frac{\dot{S}}{S} Q_A & X > 0 \\ -\eta_A X + \eta_E \frac{\dot{S}}{S} Q_A & X \leqslant 0 \end{cases} \quad (11)$$

where $\dot{Q}_A$ is the change in the amount of water delivered to agriculture, S is the water storage, $\dot{S} = \frac{dS}{dt}$ and η_A , η_E are parameters that are calibrated.

2.3.3. Optimization routine (NSGA-II)

NSGA-II presented by Deb et al. (2002) is a tool to calibrate model parameters. NSGA-II is a multi-objective optimization algorithm that simultaneously optimizes multiple objectives without being dominated by any other solution and presents optimal parameter sets as a Pareto front in the multi-objective space (Yusoff et al., 2011). The main steps of the NSGA-II method can be found in (Amirkhani et al., 2017).

The parameter setting of NSGA-II method used for calibration is shown in Table 2.

Three objective functions are defined and minimized in the optimization algorithm. The first two objectives, f_1 and f_2, are sums of squared differences between observed discharge and discharge estimated by the coupled model at gauge numbers 4 (linked to agriculture demand) and 6 (linked to environmental demand; see Fig. 4), respectively. The third objective, f_3, is the sum of the squared difference between observed and predicted unemployment rates in BLB. The calibration period is 1999–2013.

2.3.3.1. Calibration parameters. Parameters that are calibrated (see Table 3) include γ_V (time factor), parameters of community sensitivity, six parameters of the community response function and the parameter *v* of the migration equation.

3. Results and data analysis

First, the multiobjective calibration results of the socio-hydrological model are shown, including an investigation of the obtained parameter pareto optimal (non-dominated) sets in three-dimensional space of the objective functions. The non-dominated sets obtained are then used to simulate socio-hydrological responses and to validate against observed river discharge at gauges not used in calibration. Simulated agricultural water use is also validated against observed agricultural water demanded and used. Finally, the simulated community sensitivity and response function are discussed and contrasted with observed Bakhtegan Lake extents to discuss the robustness of model calibration and realism of community sensitivity in effectuating changes in lake extents in response to the degrading environment.

3.1. Calibration results

Previous research has indicated that the nature of societal parameters used, for instance of community sensitivity, makes it challenging to validate the realism of calibrated socio-hydrological models (Kandasamy et al., 2014; Pande & Sivapalan, 2017; Troy et al., 2015). Using the three non-commensurable objectives of simulating the agricultural water use, environmental water release and the basin unemployment rate, the NSGA-II optimization model provides a pareto optimal (non-

Table 2
Parameters values of the NSGA-II algorithm used in the study.

Parameter	Number/type
Population	100
Crossover rate	0.6
Crossover operator	Uniform crossover
Selection operator	Tournament
Mutation rate	0.2

Table 3
Maximum, average and minimum values of pareto-optimal parameter sets obtained from NSGA-II search algorithm (all of the parameters are dimensionless).

Parameter	Definition	Maximum	Average	Minimum	equation
K_d	Scaling factor	12.21	10.46	4.57	(9)
Vc^*	Critical community sensitivity	22.30	19.27	12.94	(9)
η_E	Translation factor	4.49	3.61	1.18	(12)
η_A	Translation factor	17.76	7.01	5.13	(12)
γ_v	Time factor	17.75	9.70	7.04	(7)
V_m	Maximum sensitivity of the particular community	127.74	117.64	85.43	(10)
ν	Factor for migration	13.17	4.30	−4.82	(2)

dominated) set of parameters that simulate the three fluxes with mutually constrained accuracies. That is, no one pareto optimal parameter based simulation can perform better in representing the observed than the simulations of all other pareto optimal parameters sets in all the three objectives (of accurately simulating agricultural water use, environmental release and basin unemployment rates).

The results obtained from the optimization of calibration parameters are summarized in Table 3.

Figure 6a compares the annual time-series of observed discharge with maximum and minimum discharge simulated for gauge number 4 in the calibration period. Due to strategic location of the Doroodzan Dam, gauge number 4 that is located downstream of this dam has been chosen to calibrate the coupled model. Fig. 6b shows the annual time-series of observed discharge of Hassanabad-Kharame (gauge number 6) that is the last gauging station before the river enters the Bakhtegan Lake.

3.2. Interpreting the inherent sociohydrological dynamics

3.2.1. Agricultural demands and discharges

Agricultural demands (corresponding to the five regions of BLB in Fig. 4) that were supplied, were used for the socio-hydrological model's validation.

The observed data used in this paper were provided by Ghafarijoo et al. (2016). The observation data (irrigation water requirements) for each demand site were determined by considering effective rainfall, evapotranspiration and the type of crop cultivated. The corresponding observed and simulated annual agricultural water supplies of the five regions are presented in Fig. 7.

The difference between observed and simulated annual agricultural water supplies can be caused by uncertainty in Ghafarijoo et al. (2016) as well as due to model and parameter uncertainty. Although the crop patterns were changed in BLB, corresponding average irrigation water requirements were kept constant and that could have affected the simulated results. It is also assumed that agricultural water demand is always met.

Similarly, six streamflow gauges not used in calibration were used to assess modeled streamflow in the basin.

Figure 8 shows validation results based on a comparison between observed and simulated discharges (at six gauge locations) in BLB (see Fig. 4). The correlation coefficient (R^2) between recorded and simulated annual discharges are between 0.99 and 0.73 while the Nash-Sutcliffe efficiency scores are between 0.95 and 0.31. This shows that the coupled model can estimate discharge reasonably well in BLB.

3.2.2. The unemployment rate, migration and population

The unemployment rate and population are two other variables that were determined by the coupled model. Fig. 9a and b show a comparison of simulated basin populations and unemployment rates in the basin, respectively. The observed values are bracketed by the uncertainty bounds of the simulations corresponding to the pareto optimal parameter sets. While the correlation between observed and mean simulated basin employment is low, a reasonably high Nash-Sutcliffe Efficiency (NSE) of 0.6 indicates that simulated basin unemployment is able to represent variability in the observed unemployment rate well.

Population figures were available only for three years to compare with the simulated results since the population census is conducted every five years. Nonetheless, the observed populations are found to be within the uncertainty bounds of the simulated results as shown in Fig. 9a. Due to a lack of unemployment rate data in the BLB, the unemployment rate of Fars province (BLB is located in this province) is used as a proxy. This and model uncertainties can be the reason for the discrepancy between the simulated and observed values of the unemployment rate in Fig. 9b. However, the variation of the simulated unemployment rate is similar to the observed unemployment rate of Iran with NSE of 0.6 and R^2 of 0.3. The variation in unemployment rate within and outside the basin also reflects in the basin outmigration.

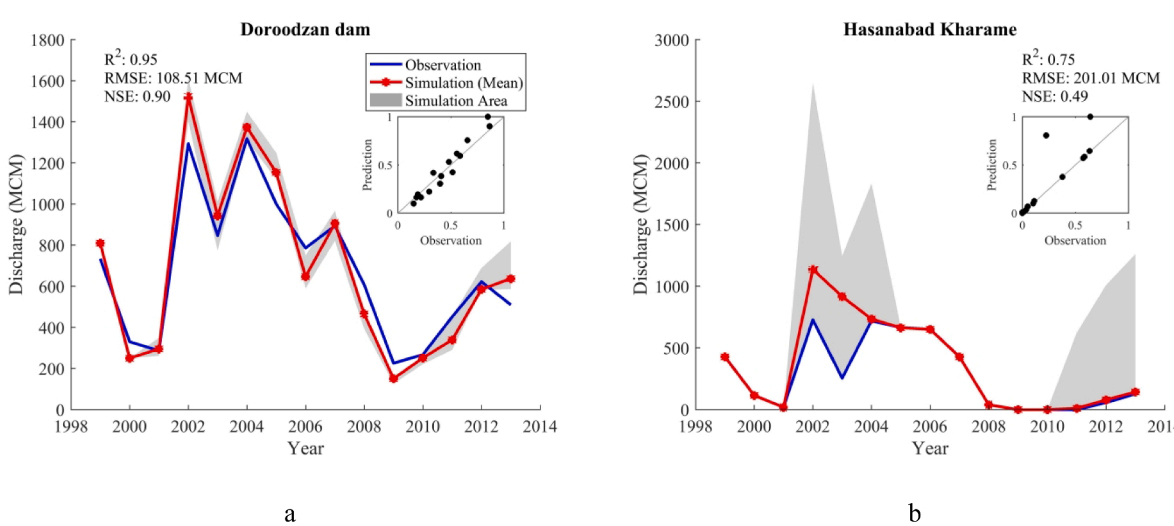

Fig. 6. Time-series of observed discharge (blue), gray area showing prediction uncertainty bounds as simulated by the pareto optimal parameter sets obtained by NSGA-II and mean simulation (red) for Gauge number 4 (a) and Gauge number 6 (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

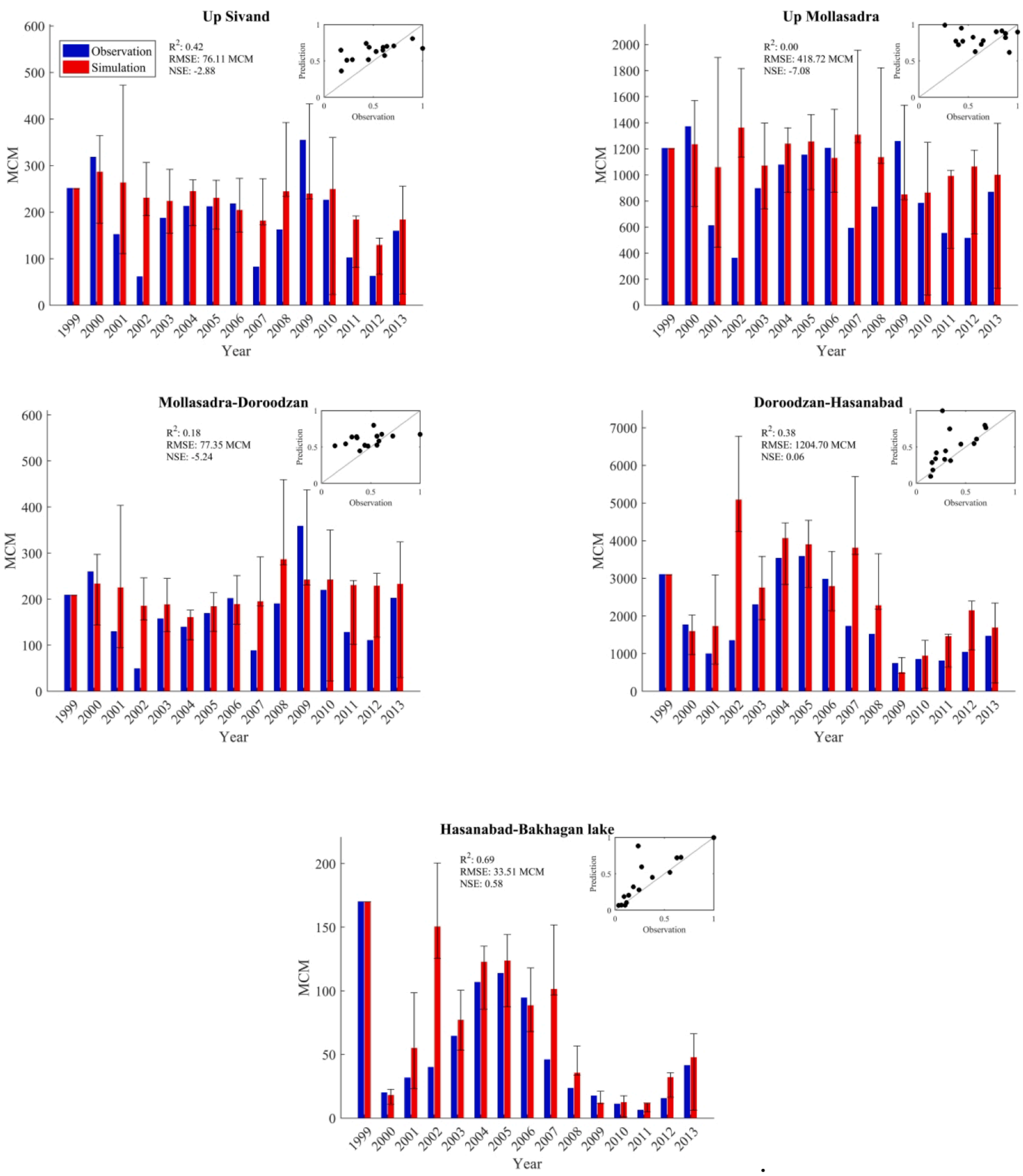

Fig. 7. Agricultural demands: observed vs simulated by the model. Uncertainty bounds correspond to the pareto optimal parameter sets while mean simulations are compared with the observed in scatter plots shown in the inset.

Figure 10 shows the mean simulated migration from 2000 to 2013. The average annual migration from BLB to the outside is between two to four thousand, which gradually declined for the most part except towards the end of the simulation period. The peaks around 2004 and 2013 (i.e. more out-migration) are noteworthy and correspond to minor revivals of Baktegan Lake when water was taken away from agriculture and given back to the environment. The simulated migration suggests that farmers partly adapted to it by migrating out of the basin.

3.2.3. *Community sensitivity and response*

The variations in the areal extent of the Baktegan Lake were processed in GEE (Google Earth Engine) using high resolution Landsat 5, 7 and 8 images and used to compare with the changes in simulated community response. Sajedipour et al. (2017) also compiled a table, shown below (Table 4), that includes the lake extents as observed by other studies. This data is also utilized to validate areal extent computations.

Tabouzadeh et al. (2016) utilized a standardized precipitation index for the analysis of drought characteristics in BLB and found that droughts occurred during 1999–2001 and 2008 In addition, Dehghanipour et al.(2019) show that, according to observed annual precipitation from 1992 to 2013, precipitation in 1999, 2000, 2001 and 2008 were 40% lower than the average during 2002–2013 in the Urmia Lake Basin. GEE results show lake extents shrinking around similar times in BLB.

Different columns of shaded areas indicate major events in operational water management from left to right:1) drought in 2000–2001; 2) community response to revive the lake in 2002; 3) transference of national lands to agricultural projects and non-agricultural projects from 2005 to 2013; 4) Mollasadra Dam operationalized in 2007, another drought started in 2008 and the Sivand Dam operationalized in 2009; 5) the community responded yet again to revive the lake that was otherwise desiccating as a result of dry conditions and operationalization of the two upstream dams upstream from 2011 to 2012. Additionally, the years 2003 to 2007 and 2012 to 2013 were non-drought periods that witnessed no community response. Fig. 11 shows that after each dry duration in the basin and heightened agricultural water demand (see

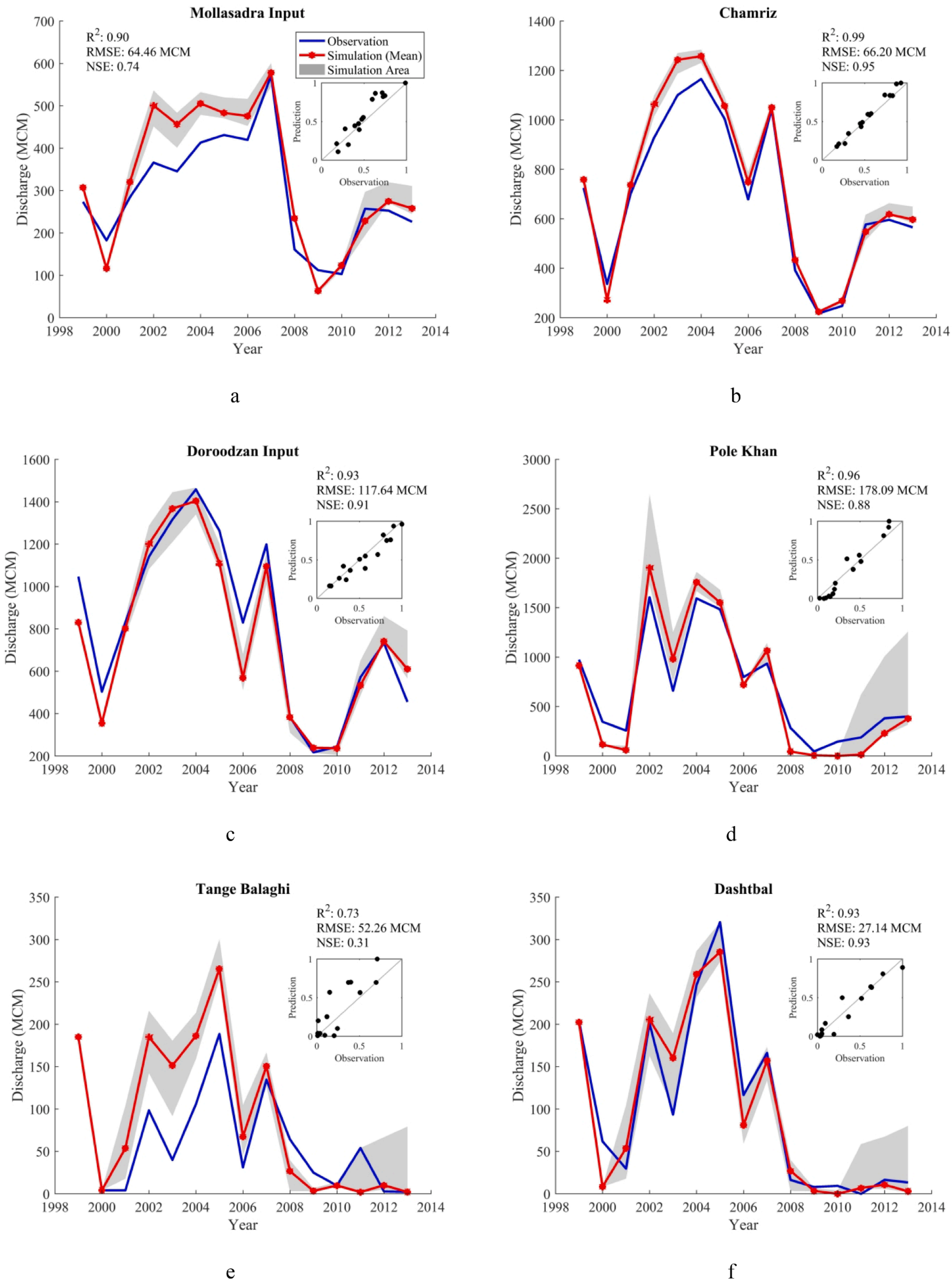

Fig. 8. Time-series of observed discharge (blue), gray area showing prediction uncertainty bounds as simulated by the pareto optimal parameter sets obtained by NSGA-II and mean simulation (red) for Gauge number 1 (a), Gauge number 2 (b), Gauge number 3 (c), Gauge number 5 (d) on the Kor river and Gauge number 7 (e), Gauge number 8 (f) on the Sivand river. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

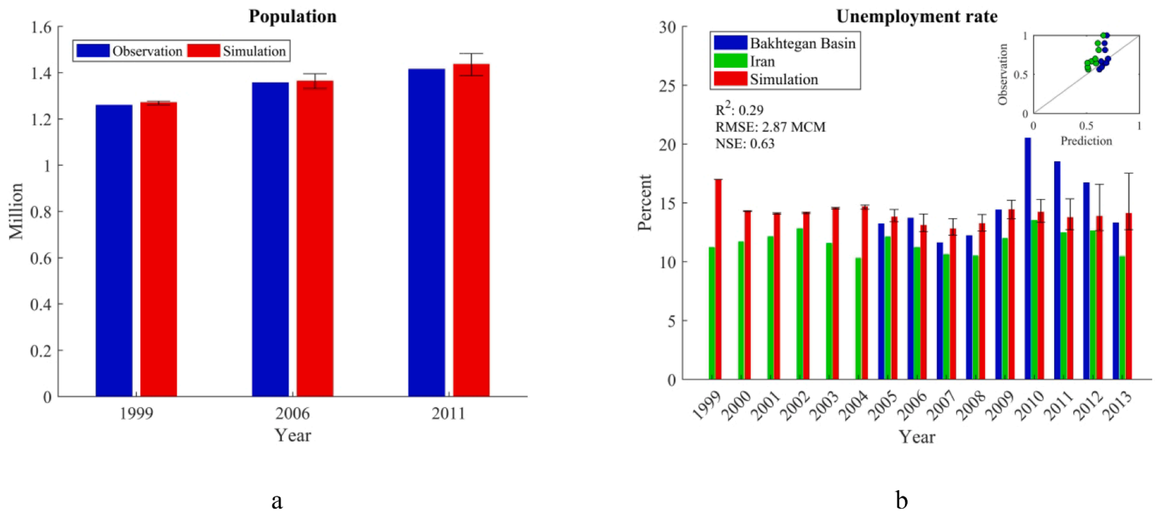

Fig. 9. a) Observed and simulated population, b) time-series of observed vs simulated unemployment rate. The uncertainty bounds correspond to pareto optimal parameter sets, while mean simulations are shown in the inset scatter plot of b).

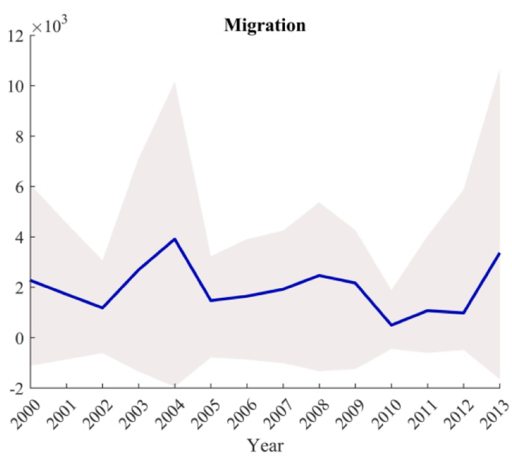

Fig. 10. Migration was obtained for BLB. Gray area corresponds to the uncertainty resulting from pareto optimal parameters sets.

Table 4
The Bakhtegan Lake areal extents on different recorded dates (Sajedipour et al., 2017).

Date	Lake area (km^2)	Reference
5/25/1998	683.3	Rafii et al. (2011)
1/26/2000	564.0	Jokar Arsanjani et al. (2015)
2/6/2000	597.0	Jokar Arsanjani et al. (2015)
2/16/2002	486.0	Jokar Arsanjani et al. (2015)
5/13/2005	761.0	Tangestani et al. (2013)
2/20/2007	443.5	Almodarresi et al. (2014)
6/15/2007	432.0	Tangestani et al. (2013)
2/20/2013	300.3	Almodarresi et al. (2014)
4/5/2013	360.0	Jokar Arsanjani et al. (2015)
9/18/2013	240.0	Jokar Arsanjani et al. (2015)

also Fig. 7), e.g. 2008 to 2010, the community responded by reducing agricultural water demand, and increasing the release of water to the lake.

Equation (6) assumes that a change in community sensitivity is proportional (with an opposite sign) to a change in the sum of income per capita and ecosystem services relative to the average of past five years. Hence a significant response towards environmental protection is expected when income per capita in the past five years has remained stable but (perhaps at the cost of) ecosystem services have severely degraded. This can be seen in Fig. 11 at 2002 and 2011. The community sensitivity begins to dissipate when ecosystem services significantly improves relative to past five years, even when income falls. This is because ecosystem services degrade to really low levels, unlike income per capita, before community responds and improvements are made.

The beliefs and norms of the community, as possible drivers of community sensitivity and response, change at time scales of generations under ordinary circumstances. The period that has been simulated also witnessed some important land use changes and lake desiccations (see e.g. Fig. 10). Based on the calibrated results, the model suggests that construction of dams and expansion of agriculture, perhaps compounded with droughts, led to heightened sensitivity. This may have risen faster than under ordinary circumstances, leading to responses within the 15 year simulation period. Also, note that community sensitivity equation has a time scale parameter, γ_V, that is calibrated on data. This encapsulates whether community sensitivity changes at a faster pace for a given case study. Calibration shows that the range lies between 7 and 17 years. This is within the data length of 15 years, meaning that community sensitivity can change within the period mentioned, and close to intergenerational time intervals of 20–25 years often considered for changes in norms over generations.

To further investigate the interpretation of this model with the events and the societal response, news from reputable domestic news agencies was examined regarding changes in local water policy. The most significant of which appeared on October 26, 2011 where the head of the Environmental Protection Agency stated that "due to the unauthorized withdrawals and wells that were dug there illegally, the Environmental Protection Agency and the Ministry of Energy followed up and took the necessary measures in this regard." He added: "It was also decided with the follow-up of the Environmental Protection Organization that the water required for this lake will be provided through the Ministry of Energy (through Dorrodzan Dam), and it seems that the problem of the second largest salty lake of Iran (Bakhtegan) will be resolved." Head of the Environmental Protection Agency also stated that almost 40 million cubic meters of new water had been released from Dorrodzan Dam in 2011 to improve the condition of Bakhtegan Lake. He also pointed out that more water should be considered for Bakhtegan Lake water rights (Environmental Protection Organization, 2011). This corroborates the interpretation of the sociohydrological model that the community responds to improve environmental quality when faced with extreme degradation and demonstrates the strength of sociohydrological conceptualization provided by Roobavannan et al (2017b).

It can be noted that the annual rainfall in most of the meteorological

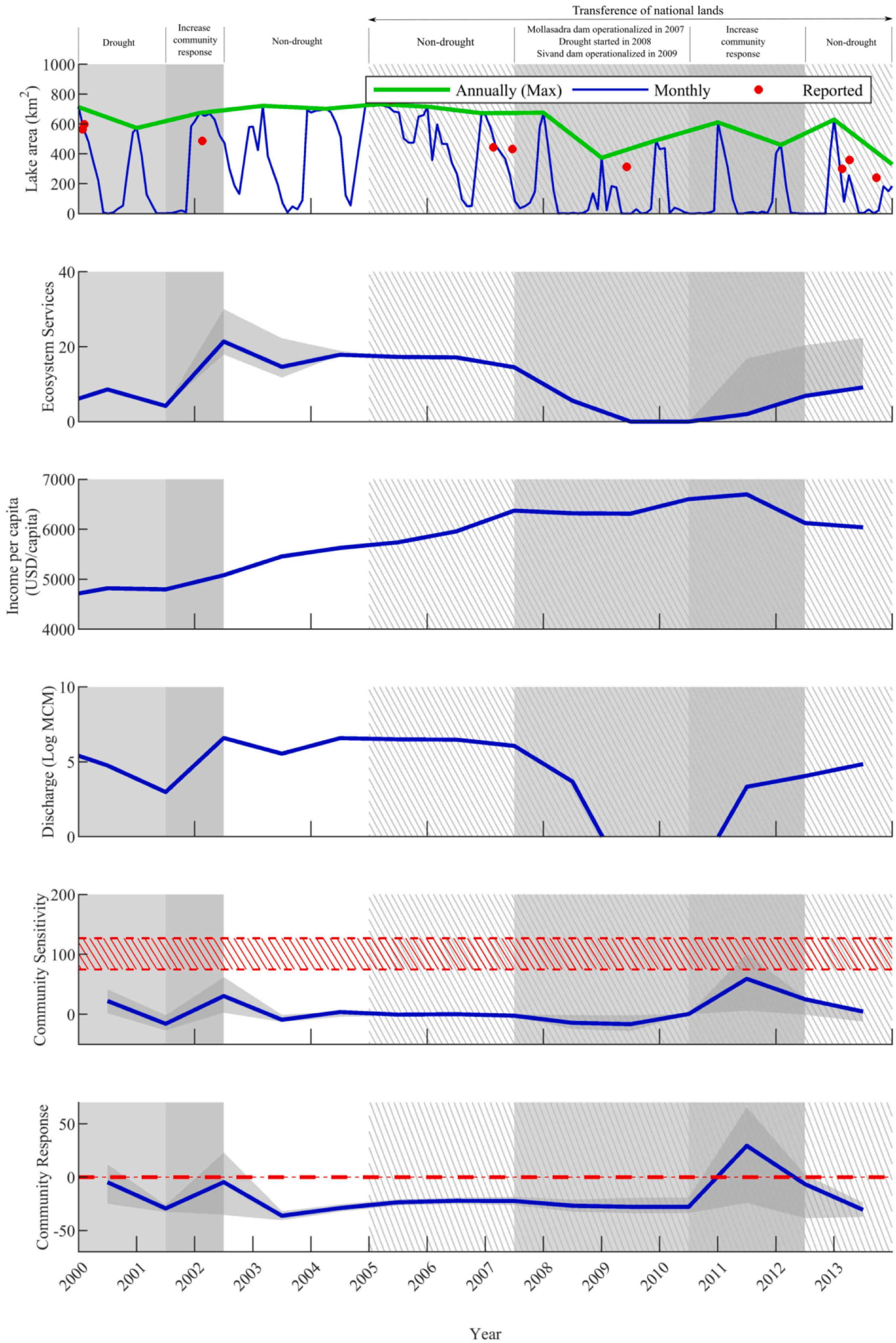

Fig. 11. Changes in Bakhtegan lake area, various related events, its effects on the provision of ecosystem services, environmental flow (log discharge), community sensitivity and community response. The changes in Baktegan Lake surface, processed in GEE, are interpreted as a result of droughts, dam operationalization, community sensitivity and community response triggering actions to revive the lake.

stations in the Bakhtegan Basin after the 2008 drought returned back to normal before the drought (Figure A2 in the Supplementary Materials). Although the amount of rainfall observed in 2011 is less than the amount of rainfall reported in most of the stations in 2010 and 2012, satellite images show that the lake area was bigger (Fig. 11). The reason for this is the release of 40 million cubic meters of the Doroodzan Dam, which had been approved by the government, and partly shows the impact of water management decisions (Nasim news, 2012). The increased flow in 2011 is also been simulated by the model (shown in Fig. 11).

As mentioned earlier, Kor and Sivand rivers have a major role to play in providing water to Lake Bakhtegan (see Figs. 1 and 3), and the existence of dams on these two rivers indicates that, even if rainfall increases, decision-makers can stop releasing water to the environment and store water in the reservoirs. Especially after the drought, the reservoirs have the capacity to save water.

Figure 1 plots the flow difference between gauge 4 and 6. First drought started in 1999 and lasted till mid- 2001, while the second drought occured in 2008. In the first drought the lake level recovery coincided with the recovery of the lake. The lake recovery around the second drought period happened with lower than normal water being allocated to agriculture to the downstream agriculture demand centers, the Doroodzan-Hasanabad region and near zero water allocated to the agriculture in Hasanabad-Bakhtegan Lake region. This is indicated by the flow difference from 2009 to 2012. Humans, particularly governments, played an important role in meeting environmental needs by regulating agricultural water and the river flows.

Indeed, community response is closely linked to ecosystem services and also lake levels as Fig. 11 shows. However, after slight revival, the community response went below 0. This is because sustained continued response also depends on the economy of the country which deteriorated after 2012. Nonetheless note that the new dams were operationalized in 2007 and 2009, before the spike in community sensitivity in 2011, not after. The spike may have also been due to concurrent drought but note that while rainfall recovered to normal levels in 2009 onwards, agriculture water demand met remained lower than before 2008. This is shown in the Fig. 1. The evidence of community response due to heightened community sensitivity in 2011 is that the Director-General of Environmental Protection of Fars Province confirmed that 40 million cubic meters were released from the Doroodzan Dam and also he said that another 40 million cubic meters were approved and were allocated as environmental water requirements.

However, field visits and local research as well as the model show that the latter allocation was not entirely implemented in the coming years due to weakening of the economy after 2012 (Tasnimnews, 2013). This also corroborates the findings of Roobavannan et al. (2020); Roobavannan et al. (2019), that changes in water policy to divert water away from agriculture and to the environment depends on how diversified the economy is.

Critical community sensitivity is a parameter that can be compared to other studies such as Elshafei et al. (2014) and Roobavannan et al. (2017a). Calibrated critical community sensitivity in BLB is more than Murrumbidgee River Basin (MRB). This means that in BLB improving society's economic condition takes priority over improving the environmental condition. The time scale of the community sensitivity parameter in BLB is shorter than in MRB, indicating that communities in BLB change their attitudes toward the environment more rapidly. Since the time scale could be influenced by outside social, economic, and political factors (Elshafei et al., 2014), accelerated changes in attitude toward the environment in BLB could have probably been caused by less stable political factors when compared to MRB in Australia. Furthermore, the factor for migration in BLB is greater than the MRB, indicating that the economy and unemployment rate have a higher impact on migration in BLB.

4. Conclusions

This paper focused on interpreting community behavior and its response under changing sociohydrological conditions such as droughts, building of dams and the transfer of lands to agriculture, in BLB in southwestern Iran. Results interpret that the community responded to the effects of drought and operationalization of dams on the lake by taking water away from agriculture and releasing it to the lake and by controlling the proliferation of unauthorized wells.

The sociohydrological model presented here provided one interpretation of change in policy, that it was due to heightened community sensitivity as a result poor delivery of ecosystem services with a strong economy to support such a decision.

Sociohydrological modeling was used to interpret changes in agriculture water supply, unemployment, migration, and population as the community adapted to changing environmental conditions. Calibration and validation results showed that the model was successfully able to simulate and interpret such past observations, suggesting that it can reliably predict future trajectories of system behavior under changing socio-economic conditions.

Although the model developed in this study is well adapted to the BLB, there were some limitations such as a lack of reliable information and modeling of groundwater resources and changes in crop patterns. These limitations can be ameliorated in the future through more observations and additional modeling of the groundwater within the presented socio-hydrological model. This increase in complexity is necessary to improve the realism of the model and is left to future research.

In the developed model, changing cropping patterns of the past are considered within the corresponding agricultural water demand calculations. However, there are currently no feedbacks from community sensitivity to crop diversification. The only feedback is to how water available is divided between water for agriculture and for environment. One way to incorporate the feedback to crop diversification can be to identify a crop mix that maximizes income for farmers for a given allocation of water and available technologies. We leave this for future research.

It should be noted that the model presented is useful for future decision-making because all possible solutions, such as crop substitution, shift to more water-efficient technologies and practices, migration of farmers, other factors that reduce water intake, have an impact on the economy of the Bakhtegan Basin and none of these factors can be considered in isolation and do not necessarily improve environmental conditions on its own. For example, we can refer to the law on the replacement of rice cultivation by other agricultural products. The lack of attention to the price of rice and alternative crops and their impact on people's incomes resulted in the legislation not being implemented. Using WEAP as the hydrological model that has the ability to consider different scenarios as well as the ability to consider changing cropping patterns, it would be useful for future research to investigate different scenarios of climate change and cropping patterns as inputs. Developed model can either estimate how much the government should spend on environmental water supply to permanently restore the lake. Consideration of the climate change scenarios and economic conditions to run the sociohydrological model can give decision-makers more accurate results. This however was beyond the scope of current study and left for future research.

Data availability statement

Data from the "Iran Water Resources Management Company, Ministry of Energy of Iran" including reservoirs operation data (Storage, Release, evaporation, etc.) are available upon request from the corresponding author. Observed discharge data are available through http://wrs.wrm.ir/amar/login.asp. Irrigation demands were calculated by Ghafarijoo et al. (2016, In Persian). Births and deaths rate data are available through https://www.worldbank.org/. Population and labor data are available through https://www.amar.org.ir. The unemployment rate in the Bakhtegan Lake Basin is available through https://amar.mpo-fr.ir/TabIndex.aspx?q=www&TabId=10407. The unemployment rate of Iran is available through https://www.statista.com/statistics/294305/iran-unemployment-rate/. Also, GEE data and Lake water surface extents are available at https://code.earthengine.google.com/d4ea51d6d294af86eddd3d529d58d138.

CRediT authorship contribution statement

Masoud Amirkhani: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Heidar Zarei:** Supervision, Conceptualization, Validation, Writing – review & editing. **Fereydoun Radmanesh:** Supervision, Conceptualization, Validation, Writing – review & editing. **Saket Pande:** Supervision, Conceptualization, Validation, Writing – review & editing.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2021.127375.

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