Water Resources Management (2024) 38:2753–2772
https://doi.org/10.1007/s11269-024-03786-z

# Agricultural Water Resource Management in the Socio-Hydrology: A Framework for Using System Dynamics Simulation

**Fatemeh Javanbakht-Sheikhahmad[1] · Farahnaz Rostami[1] · Hossein Azadi[2] · Hadi Veisi[3,4] · Farzad Amiri[5] · Frank Witlox[6]**

Received: 24 July 2023 / Accepted: 8 February 2024 / Published online: 26 April 2024

## Abstract

Population growth, coupled with climate and social shifts, has resulted in a global phenomenon of water scarcity. Yet, the effect of social factors on water resources has been poorly studied. Hence, this study aimed to identify the key parameters in social systems that significantly impact hydrological system change and presents the best scenario for water management. The system dynamic (SD) approach was employed in this research to construct a combined framework of policies based on scenarios, which aimed to ensure social sustainability and coupled human-water systems. For this purpose, the SD model was simulated on the Gavshan Basin in the west of Iran for the long-term period 2020-2050. The results indicate that the water resources in the Gavshan Basin cannot meet the growth of the population. Meanwhile, about 20% of the water stored in the Gavshan Dam is not effectively used and flows out of the irrigation network as wastewater. The result of the sensitivity analysis showed that in scenarios 3 and 4, the policy of wastewater reuse in the agricultural sector significantly increases available water resources, has a major impact on water supply, and increases crop yields. These findings can be applied by policy-makers. Instead of making efforts only to change hydrological systems, policies need to first focus on socio-hydrology systems sustainability. It is suggested that national organizations' support should be implemented to prevent the adverse consequences of wastewater reuse in agriculture and reduce treated wastewater risks.

**Keywords** Hydrological cycle · Irrigated agriculture · Scenario-Based simulation · Social sustainability · Water scarcity

---

✉ Farahnaz Rostami
f.rostami@razi.ac.ir

[1] Department of Agricultural Extension and Education, Razi Univeristy, Kermanshah, Iran

[2] Department of Economics and Rural Development, Gembloux Agro-Bio Tech, University of Liège, Gembloux, Belgium

[3] Kirchhoff Lab, Penn State University, University Park 16802, PA, USA

[4] Department of Agroecology, Shahid Beheshti University, Tehran, Iran

[5] Department of Industrial Engineering, Kermanshah Univeristy of Technology, Kermanshah, Iran

[6] Department of Geography, Ghent University, Ghent, Belgium

## 1 Introduction

The worldwide populace is increasing rapidly, and projections indicate that by 2030, if the existing water administration methods persist, the planet will confront a 40% insufficiency between projected demand and accessible water supply (Bo et al. 2021). Moreover, persistent water shortage, hydrologic unpredictability, and severe climatic occurrences (such as deluges and arid spells) are regarded as major menaces to worldwide well-being and societal endurance (Kellner 2021). Hence, the interdependence between the hydrological system and the human system renders the regulation of water resources more intricate (Sriyono et al. 2021). Conversely, water shortage has emerged as a significant impediment to the advancement of society and poses a peril to sustenance in expanding regions across the globe (Liu et al. 2020). Conversely, the choices taken by water resource executives have the potential to generate either benefit or hardship for the populace and may even steer society towards unrest and activism (Stosch et al. 2022). Neglecting the correlation between the human-water systems could result in the breakdown of water governance (Sriyono et al. 2021).

In light of the growing problems of water scarcity caused by human activities, water specialists have begun to tackle the constraints of water management by considering the interdependent interactions between society and water, and by promoting a stronger integration of hydrology and social science (Kellner 2021). The discipline of socio-hydrology holds great potential in the field of water resource management, as it seeks to uncover the complex interplay and reciprocal influences between natural systems and human activities, with the ultimate goal of promoting sustainable water usage (Vanelli and Kobiyama 2020). Socio-hydrology endeavors to observe, comprehend, and forecast the dynamic interrelationships and interdependence between water and humans (Xia et al. 2022).

Most research on socio-hydrology (e.g., Xia et al. 2022, 2018; Penny and Goddard 2018) has elucidated interconnected human and water systems via numerical methods and conscientious endeavors to apprehend socio-water interrelations and response through mathematical models, mainly as non-linear differential models. Some socio-hydrological studies have tried to model the complex dynamics between coupled human-water systems using various modeling methods such as System Dynamics (SD) modeling (Dong et al. 2019; Elsawah et al. 2017; Lindqvist et al. 2021), Agent-based modeling (Molajou et al. 2021), and Monte Carlo simulations (Jeong et al. 2020). The SD technique has found an explicit application in socio-hydrological studies compared to all the modeling techniques described in this review. The study of SD involves the use of model simulations to comprehend the dynamic behavior of intricate systems during their evolution. This technique has been widely used in water resources management, e.g., dynamic water resource management in China (Dong et al. 2019), urban water supply in Pakistan (Bano et al. 2022), ecosystem service provision of urban water in Finland (Lähde et al. 2023), and modeling of wastewater treatment plants (Noutsopoulos et al. 2020). Moreover, SD has been employed to illustrate the enhancement of embankment procedures for flood control (Luu et al. 2022). However, some research (e.g., Behboudian et al. 2023; Molajou et al. 2021) has demonstrated the ability of socio-hydrological systems to withstand severe occurrences. The SD technique is a way to understand complex system behavior over time and identify feedback loops and time delays that influence total system behavior (Sun et al. 2017). Studying how a system changes over time is one of the advantages of SD modeling. SD models in socio-hydrology systems represent system components that change over time (Luu et al. 2022).

Socio-hydrological models that have been developed based on SD help to understand the process and interactive feedback between human and water systems (Xu et al. 2018).

These models can be employed to forecast the potential future developments over the next few decades, based on the current state of the socio-hydrological system (Melsen et al. 2018). While most previous studies (e.g., Luu et al. 2022; Jeong et al. 2020; Dong et al. 2019) have concentrated exclusively on quantitative modeling and the development of hydrological components, only a limited number of studies have made efforts to operationalize social concepts in water management. In other words, the processes and interactions between social and hydrological systems are not well-defined in mathematical terms in socio-hydrology studies (Mostert 2018; Xu et al. 2018). Therefore, the major limitation of the implementation of social components in socio-hydrological models is the formulation of social components (Massuel et al. 2018).

In order to fill this gap, the present research addresses the formulation of social interactions in socio-hydrology research. In Fig. 1, the study framework was designed to simulate the interactions between hydrological and social systems. The aim of this study is to present a new hybrid method that extends the socio-hydrology knowledge around the concept of economic, agricultural, and social sustainability. Social sustainability considers and reflects on the question of quality of life, participation, health, trust, responsibility, security, and solidarity across residents of a Gavshan basin in the west of Iran. Accordingly, the research questions are as follows:

(1) How is the process of the evolution of the human-water system?
(2) How is the prediction of the trajectories of social, hydrological, agricultural, and economic systems?
(3) What is the best scenario for water resource management from the perspective of socio-hydrology?

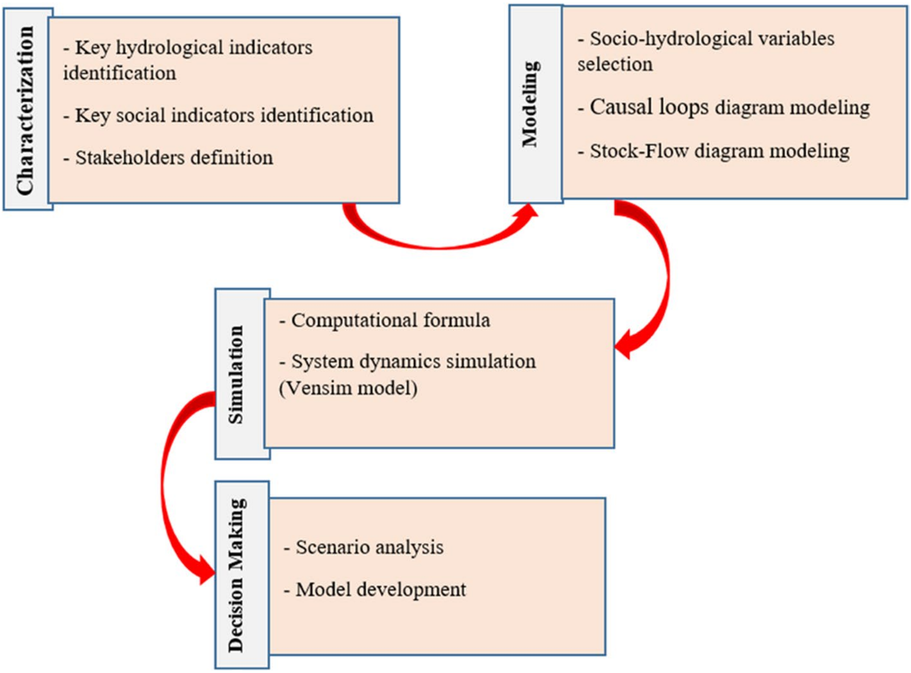

**Fig. 1** Conceptual framework of the study

## 2 Materials and Analysis

### 2.1 Study Area

Gavshan catchment with a 7736 $km^2$ area is located in Kermanshah province, in the west of Iran. In Spring, approximately half of the Gavsahn dam's capacity is filled for a duration of three months. The volume of the Gavshan dam fluctuates between 60 and 450 ($106m^3$) based on factors such as rainfall, input, vaporization, and flow (Kermanshah Regional Water Authority 2020). Gavshan dam was built to give household water to the cities of Kermanshah and Kamiyaran, which have a total population of two million people, to give agricultural water to 31,000 (ha) of the Bilevar and Miandarband plain lands, and to generate 9.2 MW of electricity (Fig. 2). In the Gavshan Basin, agriculture serves as the primary occupation of the residents and constitutes the foundation of the local rural economy. There are about 11 agricultural pumping stations that are used to pressurize irrigation. Therefore, agriculture is the most important factor influencing social and hydrological status and water scarcity in Kermanshah province (Kermanshah Regional Water Authority 2020). The reason for selecting this region is the low performance of the Gavshan irrigation network.

### 2.2 Data Collection and Analysis

In this study, the data was acquired through a two-step process. In the first step, data regarding the societal aspect was gathered via the use of questionnaires. To select farmers, a multistage stratified random sampling technique was used. The statistical population consisted of farmers who used the irrigation Gavshan network (N= 120) (Kermanshah Regional Water Authority 2020). The sample size was determined at 87 farmers (S = 87) based on Krejcie and Morgan's table (Krejcie and Morgan 1970). The closed-questionaries included 53 questions related to the social sustainability components. Five experts who had a good knowledge of the topic/study area were consulted on the questionnaire design and content validity before the data collection. The reliability of the questionnaire was assessed by the reliability coefficient and the Cronbach's alpha was above the conventional level of 0.7. After filling out the questionnaires, the cognitive framework of the socio-hydrology system was utilized to derive hypotheses regarding the interplay between hydrological and social factors. In the second step, the model input, like daily weather data from 1990 to 2020 including temperature and precipitation, was obtained from the Kermanshah Meteorological Station (2022). The populace statistics were computed based on population surveys conducted by the Statistical Center of Kermanshah (2020) between 2000 and 2020. The agricultural and economic data were estimated using reports from the Kermanshah Agricultural Jihad Organization (2020).

### 2.3 Research Method

System Dynamics (SD) models offer a conceptual framework to depict non-linear interrelationships, explore the connections and reciprocal influences among system elements, and model water management approaches. SD models illustrate cause-and-effect loops of a system in a network, which tracks the evolution of cause-and-effect variables and simulates the dynamics of the variables over time (Dong et al. 2019). The fundamental steps involved in SD

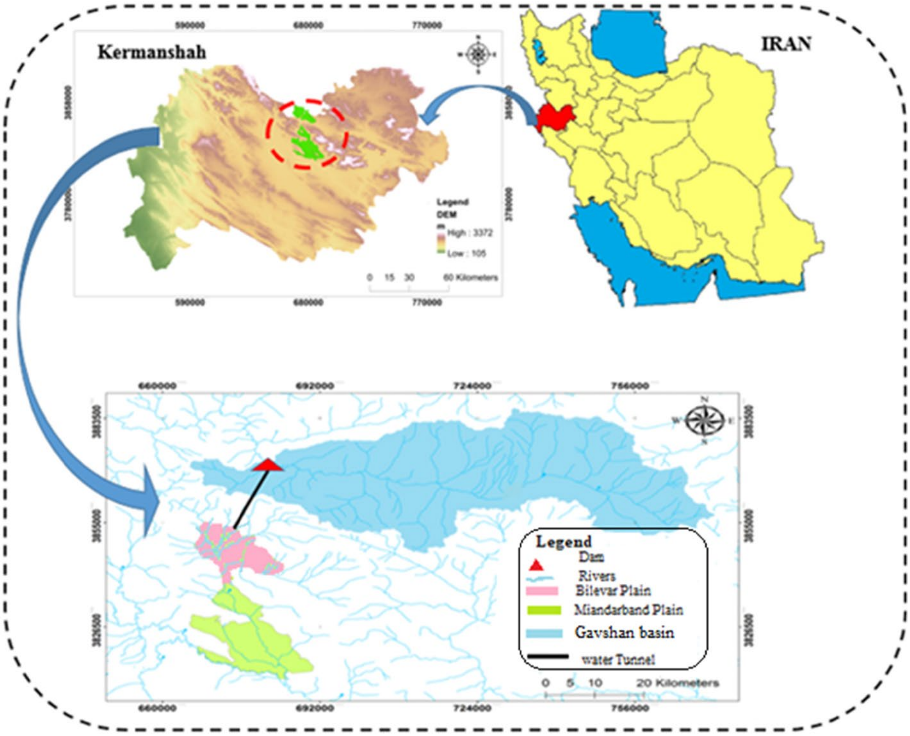

**Fig. 2** The Gavshan Basin (Kermanshah Regional Water Authority 2020)

modeling include identifying the variables and creating dynamic connections between them using a Causal Loop Diagram (CLD). The SD model comprises five fundamental kinds of variables: a stock variable (S), flow (F), a rate variable (R), an auxiliary variable (A), and an information arrow. Stock variables (also known as levels, accumulations, or state variables) accumulate information regarding inflow and outflow at a specific time (Eq. 1). Stock and flow variables are a fundamental element of a stock-flow diagram. In the SD models, stocks are used to show the real-world processes (e.g., water resources, people, stocks of material). Stock variables define the static part of a dynamic system. Flow variables define how the values of stocks change over a period of time. The rate variable measures stock changes between two consecutive times. Auxiliary variables denote the decision-making mechanism, and information arrow data signifies the correlation between two variables (Liu et al. 2020).

$$S\,(t) = S_0 + \int_0^t \left(\sum \text{Inflow} - \sum \text{Outflow}\right)dt \tag{1}$$

In the equation above, S(t) denotes the amount of the stock variable at a given time t, and $S_0$ represents the initial value of the stock variable. The inflow and outflow refer to the input and output of the stock variable over the time period (0, t).

### 2.3.1 Socio-Hydrological Hypothetises

In Fig. 3, a causal loop diagram (CLD) was formulated to specify the feedback circuits and to recognize the association links among the elements of the socio-hydrology system. The CLD represents the relationships between the variables in terms of positive (+) or negative (-) polarity (Lin et al. 2020). In the reinforcing Loop (R), a positive correlation suggests that a decrease (increase) in variable A results in a decrease (increase) in variable B. Balancing Loop (B) indicated a negative correlation between variables A and B. Therefore, the balancing Loop denotes a reverse correlation between the root cause and the reliant variable, where a decrease (increase) in the root cause will result in an increase (decrease) in the reliant variable (Elsawah et al. 2017). In Fig. 3, the reinforcing and balancing loops are shown by R and B. Based on Fig. 3, a surge in runoff caused by rainfall and river inflow amplifies the surface water flows, soil moisture level, and groundwater volume, which in turn boost the dam storage via these reinforcing feedback loops (R1, R2, R3). Increased ET has balancing feedback on both soil water content and precipitation (B1, B2). Whilst the infiltration process augments the quantity of aquifer, the restoration of the aquifer through groundwater recharge diminishes the current of the river and has an adverse impact on the stream of surface water (balancing loop of B3).

The transfer of base flow from underground aquifers to the dam reservoir reduces the volume of groundwater (B5). Furthermore, the expansion of the population results in a surge in household water usage and a rise in the demand for sustenance. Following the food supply for the growing population, the agricultural water demand also increases. Furthermore, increasing the volume of dam reservoir water and access to water causes the area under cultivation of water crops to increase. Cultivating more areas of agricultural land increases the withdrawal of water stored in the dam. Increasing the withdrawals from the reservoir has a balancing effect on the cultivated area and returns the change of land to its base state (B6). For residents of the Gavshan basin whose economy and livelihood depend on agriculture, the agriculture sector is more effective in increasing income and strengthening the economic system. In the same way, the increase in the amount of crop yield has a reinforcing effect on the GDP of the region and population growth (R4). Increasing the cultivation of agricultural products, in addition to increasing income, creates employment and increases access to food. These elements as reinforcing loops of the socio-hydrology system have a positive effect on the important indicators

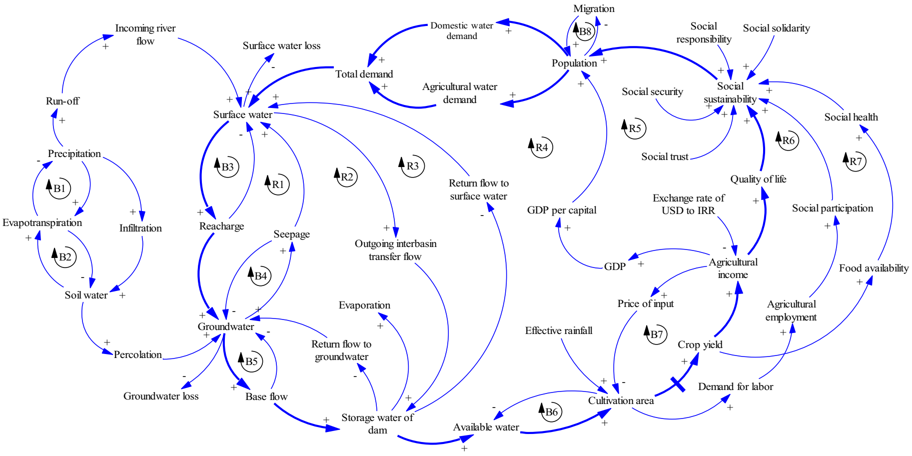

**Fig. 3** Causal loops diagram of the socio-hydrological system. Source: findings of research

of social sustainability, including quality of life, social participation, and social health, and as a result, have a positive effect on population changes (R5, R6, R7). Time lag is an important part of the socio-hydrological system. Time lags reduce the information that systems can use to respond to the environment and complicate the dynamics of the system (Sun et al. 2017). In Fig. 3, time delay was considered between cultivated area and crop yield.

### 2.3.2 Stock-flow diagram (SFD) models

In order to develop the socio-hydrology model, first, the state-flow structure of the model was drawn in the Vensim software (Fig. 4). Then the interactions between variables (stock variables and auxiliary variables) and the values of parameters (constant variables) were simulated. In the stock-flow diagram model presented in Fig. 4, there are 88 variables in the model: 10 stock variables, 21 rate variables, 3 exogenous variables (model inputs), 12 auxiliary variables, and 42 constant variables (model parameters). Variables and the mathematical formulation are reported in Appendix Table 2.

Climatic change will intensify the hydrological cycle, leading to changes in the annual water storage in the dam. Hence, in this study, the annual time step unit was used to simulate the model. The model has simulated from 2010 to 2050, and the horizon of the simulation program was 30 years. In the stock-flow model, relationships between variables are mainly described by differential equations. Mathematical equations can be derived based on evidence or experience, survey/empirical data, and logical inferences (Rebs et al. 2019).

### 2.3.3 Socio-Hydrological Equations

a) **Hydrological Variables Equation:** It is presupposed that the Gavshan dam reservoir will provide water for household and farming usage, concerning the factors of the hydrological system. The surface water considers the incoming flow volume ($F_{inc}$ (t), $10^6m^3month^{-1}$), groundwater recharge ($R_{gr}$ (t)), and outgoing interbasin transfer flow ($F_{int}$ (t)) (Eq. 2). The Gavshan Dam receives water replenishment from both precipitation and runoff, while the transfer of water between basins occurs through the flow of the Gaveh River. This refers specifically to the initiative of transferring water from the Jamishan dam to the Gavshan dam.

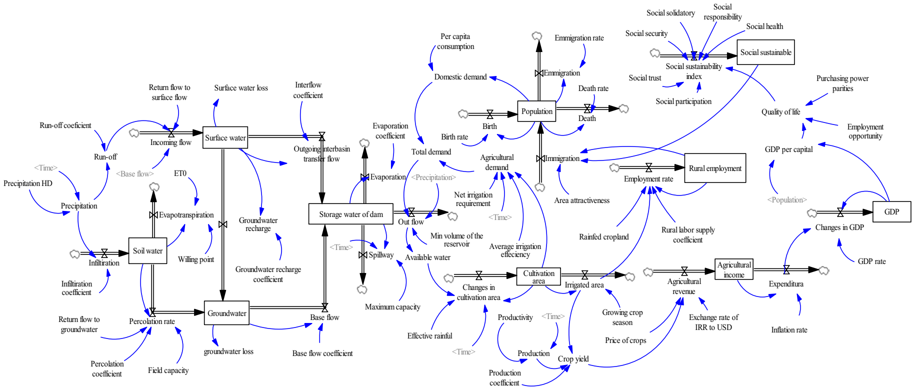

**Fig. 4** Stock-flow diagram of the socio-hydrological system, Source: findings of research

$$V_{sur}(t) = V_{sur}(t_0) + \int_0^t \left(Fin_c(t) - R_{gr}(t) - F_{int}(t)\right) \times dt \tag{2}$$

Referring to Eq. (3), the stock variable measure of the soil water formula comprises the volume of soil water, infiltration, ET, and percolation. Infiltration (I (t)) is evaluated by the product of precipitation amount (Pre (t)) and an infiltration coefficient (Cin). As shown in Eq. (4), for measuring ET, reference evapotranspiration of crops ($ET_0$) is calculated by multiplying by the volume of the soil water (Xiang et al. 2020). The WP is the threshold of the minimum amount of soil moisture that is necessary for the plant to avoid wilting.

$$V_{soil}(t) = V_{soil}(t_0) + \int_0^t (I(t) - Per(t) - ET(t)) \times dt \tag{3}$$

$$ET(t) = ET_0 \times \left(V_{soil}(t) - WP(t)\right) \tag{4}$$

Groundwater ($V_{gro}$ (t), $10^6 m^3 month^{-1}$) was modeled using the groundwater recharge ($R_{gr}$), percolation rate ($Per_{rate}$), and base flow ($F_{base}$). Base flow increases when water is transferred from a different watershed (Conant et al. 2019).

$$V_{gro}(t) = V_{gro}(t_0) + \int_0^t \left(R_{gr} + Per - F_{base}\right) \times dt \tag{5}$$

$$F_{base}(t) = V_{gro}(t) \times C_{base} \tag{6}$$

Storage water of the Gavshan dam (SWD (t), $10^6 m^3 month^{-1}$) as a stock variable, plays an extremely major role in the agricultural water supply and storing water for domestic demand. Eq. (7) is the calculation formula of water storage, base flow ($F_{base}$), evaporation (E (t), and outgoing interbasin flow ($F_{int}$) are inflow to dam storage, where ($F_{out}$) is the water flowing out the stored water of the dam, S (t) is the spillway of the dam.

$$SWD(t) = SWD(t_0) + \int_0^t \left(F_{base} + F_{int} - E - F_{out} - S(t)\right) \times dt \tag{7}$$

$$S(t) = Max_{cap}(t) - SWD(t) \tag{8}$$

when the reservoir reaches its capacity, water will flow through the spillway (S (t)) (Eq. 8).

b) **Socio-economic equation:** Population models (P (t)) as a stock variable usually start with four key variables (four demographic processes) including birth (B (s)), death (D (s)), immigration (Im), and emigration (Em). The population affects domestic water demand (DWD (t)). According to Tehreem et al. (2020), population increase due to per capita consumption (PCC (t)) increases the demand for water.

$$P(t) = P(t_0) + \int_0^t (B(s) + Im - D(s) - Em) \tag{9}$$

$$DWD(t) = P(t) \times PCC(t) \tag{10}$$

Within the socio-hydrological models, the Cul equation, as introduced by Rahman et al. (2019), is utilized to express the cultivated area. It should be noted that if a particular land parcel is utilized twice within the same year, its area will be counted twice, as mentioned by Zhou et al. (2021). Therefore, the Cul equation that exhibits the cultivated area's dynamics is presented as follows:

$$\mathrm{Cul(t)} = \mathrm{Cul}\left(\mathrm{t}_0\right) + \int_0^{\mathrm{t}} \left(\mathrm{C_{cul}(t)} - \mathrm{I_{rr}(t)}\right) \times \mathrm{dt} \tag{11}$$

where Cul (t) denotes the cultivated area, Ccul (t) represents the alteration rate of Cul, and Irr (t) denotes the irrigated area within the basin.

FAO (https://www.fao.org/3/s2022e/s2022e08.htm) has provided two empirical equations for determining the proportion of the overall precipitation that is used efficiently.

$$\mathrm{P_e} = 0.8 \times \mathrm{P} - 25 \ \ \mathrm{ifP} > 75\mathrm{mm/month} \tag{12}$$

$$\mathrm{P_e} = 0.6 \times \mathrm{P} - 10 \quad \mathrm{if\ P} < 75\mathrm{mm/month} \tag{13}$$

In the equations above, P represents the amount of precipitation (mm/month) and Pe denotes the amount of efficient precipitation (mm/month). Farming, in conjunction with its related industries, stands as a primary means of subsistence in the Gavshan river basin. The annual agricultural earnings per unit of work (AI (t)) in farming equates to the labor executed by a single individual who is fully engaged in farming activities. To calculate this measure, we utilized agricultural income (AR (p)) and expenses (Ex (p)), as shown in Eq. (14).

$$\mathrm{AI\,(t)} = \mathrm{AI}\left(\mathrm{t}_0\right) + \int_0^{\mathrm{t}} \left(\mathrm{AR\,(p)} - \mathrm{Ex\,(p)}\right) \tag{14}$$

Gross Domestic Product (GDP) is the most frequently utilized indicator for economic activity. Per capita GDP ($\mathrm{PC_{GDP}}$) is derived by dividing the nominal GDP by the overall populace of a nation (Fatmawati 2022).

$$\mathrm{PC_{GDP}} = \mathrm{GDP\,(t)/P\,(t)} \tag{15}$$

c) **Social sustainability equation:** The social sustainability equation was used to check the state of social indicators dynamics in the Gavshan watershed. The important indicators of social sustainability are social participation, social responsibility, social health, quality of life, social security, social trust, and social solidarity (Popovic et al. 2017). Thangiah et al. (2020) showed that income affected the improvement of the quality of life, so this study chose the quality of life index as an exogenous variable. Despite the numerous measures suggested to assess social sustainability, there is a dearth of supportive data for these indices. This issue is widespread in socio-hydrological system modeling owing to the absence of quantifiable information on social elements (Mostert 2018). To address this predicament, this investigation conferred quantitative importance on social sustainability in the Gavshan basin. First, a questionnaire was developed to measure social sustainability, and by survey method, nominal numbers 1 and 2 were assigned to the answers. A score of 1 indicates a positive answer (Yes) and a score of 2 indicates a negative answer (No). In the same way, the positive answers were evaluated based on Eq. 16. Dynamics between social sustainability components are simulated based on the experimental formulas.

$$I_i = Y/N \times 100 \tag{16}$$

In the equation above, ($I_i$) indicates the number of items of indexes, (Y) is the total number of positive responses to the desired item, and (N) is the total number of respondents.

# 3 Results

## 3.1 Validation and Calibration of the Socio-Hydrology Model

To evaluate the policy scenarios, first, it is necessary to have confidence in the calibration of the SD model; if the simulated model represents the real process of the system, it can be used for future prediction. In this research, validation of the model was performed through dimensional consistency tests, structural verification testing, and behavioral pattern tests with available observational information. All equations of the socio-hydrology model were correctly fitted into the dimensional test by the unit check tool in Vensim software. Assessment of structural testing is a verification that is done through qualitative assessment. To conduct structural testing, evaluators or designers may be invited to evaluate the structural correlation between the causal feedback loops incorporated in the SD model (Kurnianingtyas et al. 2019). In this study, the structure of the model (including boundaries, dynamic interactions, relationships between hydrology and social components, and parameters) was confirmed by experts in the fields of water management and experts in the agricultural management office, and they declared that the created model reflects the real structure of the socio-hydrology system. Behavioral testing determines how the trend of the simulated data matches with the historical data. To validate the system behavior in estimating precipitation, the historical data were examined (Fig. 5). The authentication relies on regression investigations in which credible cause-and-effect connections have been detected among constituents. The determination coefficient (R2=0.98) exceeded 0.7 in this instance (Fig. 5).

## 3.2 Analysis of Scenarios

The key variables' behavior of the socio-hydrology model was simulated based on the policy scenarios for the years 2010-2050 (Table 1). Using Table 1 as a reference, several situations were created to comprehend the workings of social and hydrological systems. In the base scenario, current environmental conditions were considered the same without any change (Table 1).

## 3.3 Analysis of Sensitivity

The sensitivity analysis of the SD model was checked using the Synthesis tool of Vensim software. In Fig. 6, the sensitivity of hydrological variables including the volume of surface water, the volume of incoming water, the volume of groundwater, and the storage volume of the dam towards to exogenous parameters (e.g., precipitation, flow coefficient, evaporation from the dam reservoir, infiltration, percolation, irrigation water, and per capita water consumption) are presented. The results show that the model's output is sensitive to the change of parameters and that the change of parameters of one system can affect the

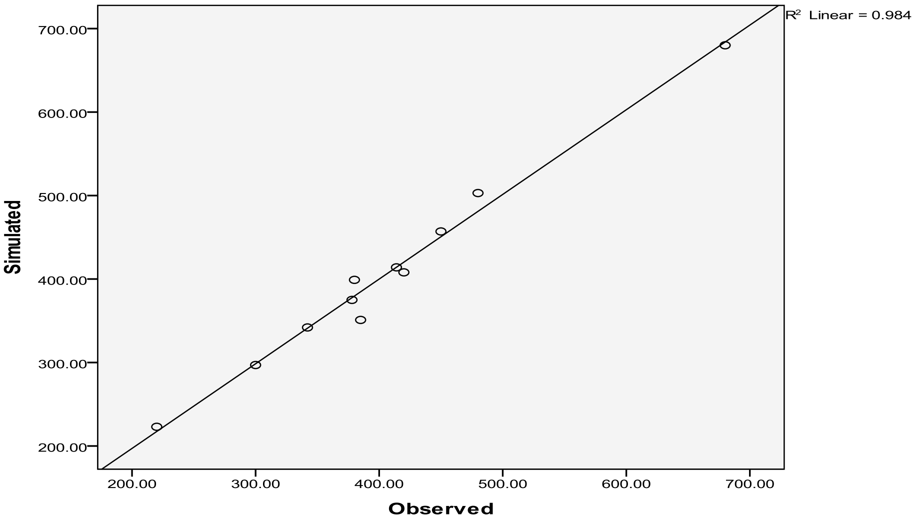

**Fig. 5** Assessment of precipitation data and simulation outcomes from 2010 to 2020. Source: findings of research

**Table 1** Designing socio-hydrological scenarios

| Scenario | Description |
|---|---|
| Baseline | Current environmental conditions within the basin would remain the same without any change (precipitation rate is 200 mm/year, the average temperature is 15 ℃, the population growth rate is 1.4%, average irrigation efficiency is 45%, per capita water consumption is 230 $m^3$/person/day, surface water loss is 37 million $m^3$ ($Mm^3$), return flow to the surface resource is 1.6 $Mm^3$, productivity is 3 ton, and social participation is 45%). |
| Scenario 1 | Irrigation efficiency increases by 55%. |
| Scenario 2 | Irrigation efficiency increases by 60%, per capita water consumption decreases by 215 $m^3$/person/day, implementation of educational programs and promotion of social participation to 55 percent. |
| Scenario 3 | Irrigation efficiency increases by 65%, per capita water consumption decreases by 210 $m^3$/person/day, wastewater reuse in agriculture to 25 $Mm^3$, and productivity increases by 4 tons/ha in 2025. |
| Scenario 4 | Irrigation efficiency increases by 70%, per capita water consumption decreases by 200 $m^3$/person/day, wastewater reuse in agriculture to 30 $Mm^3$, productivity increases by 5 ton/ha in 2027, and surface water loss decreases by 10 $Mm^3$. |

Findings of research

evolution of stock variables in another system. The behavior pattern of the water resources variables is shown in Fig. 6. The results show that with the constant environmental and social conditions, under the baseline, the volume of groundwater, surface water, and dam reserves will decrease. Meanwhile, the volume of surface water is expected to decrease from 22 $Mm^3$ in 2020 to 7 $Mm^3$ in 2050 (Fig. 6b), and the volume of groundwater will decrease from 5 $Mm^3$ in 2020 to less than 1 $Mm^3$ in 2050 (Fig. 6d).

Based on scenarios 3 and 4, water recycling and using treated effluent in agriculture directly affect the storage water. For the simulation period, the volume of inflow for

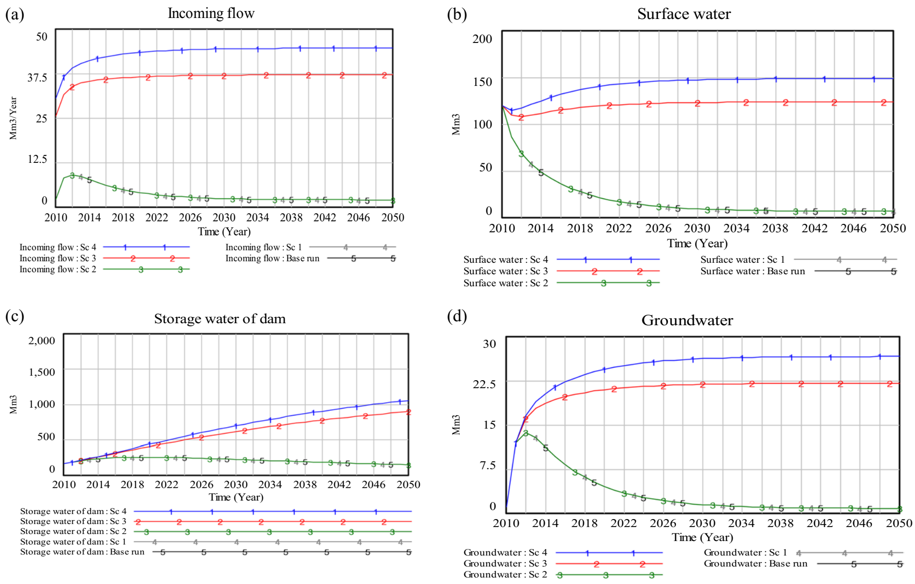

**Fig. 6** Behaviour of hydrological variables under five scenarios: (**a**) incoming flow, (**b**) surface water, (**c**) storage water of the dam, (**d**) groundwater. Source: findings of research

scenario 3 is estimated from 2 Mm$^3$ in 2010 to 37 Mm$^3$ in 2050 (Fig. 6a), a difference that constitutes about 19% of the inflow. This indicates that wastewater reuse has a high impact on the surface flow and the volume of stored water in the Gavshan dam (Fig. 6b). In the same way, wastewater reuse in agriculture increases groundwater recharge and causes the volume of groundwater to increase. As shown in Fig. 6, during the simulated period in the base scenario, withdrawal from the dam reserves is increasing, and the volume of outflows is more than the volume of inflows. The outflows indicate a significant reduction in the volume of water storage in the Gavshan dam in the future. At the beginning of the simulation period, withdrawal water from the reservoir was 170 Mm$^3$; with a growth of 50% in 2019, it reached its maximum amount of approximately 256 Mm$^3$ (Fig. 6c).

Fig. 7 illustrates the outcomes of the sensitivity tests for essential social parameters in the model, such as population, water requirements, agricultural productivity, employment, GDP, and social durability. These parameters signify the social, economic, and agricultural systems and can exert a considerable influence on the hydrological system. The simulated result of the stock variable of the population is shown in Fig. 7a. The annual population growth rate in the present study is 1.6%, which is assumed a constant value from 2010 to 2050. With this growth rate, the population was 2.04 million people in 2017, and it will be 12 million people in 2050. Domestic water demand is influenced by population and per capita water consumption in urban and rural areas. According to the population growth trend in the studied area, domestic water demand will increase. As shown in Fig. 7b, the domestic water demand has an increasing trend. The value of this variable is 66.240 Mm$^3$/year at the beginning of the simulation period, and it will be 99.202 Mm$^3$ /year with a growth of 20.8% in domestic demand at the end of the simulation period. Behavioral patterns of agricultural water demand are also a function of population. Therefore, the observed trend for this variable is similar to the trend of domestic water demand behavior (increasing). Considering that the per capita consumption of domestic water in Kermanshah is 230 (m$^3$day$^{-1}$person$^{-1}$) and is about 26 (m$^3$) more

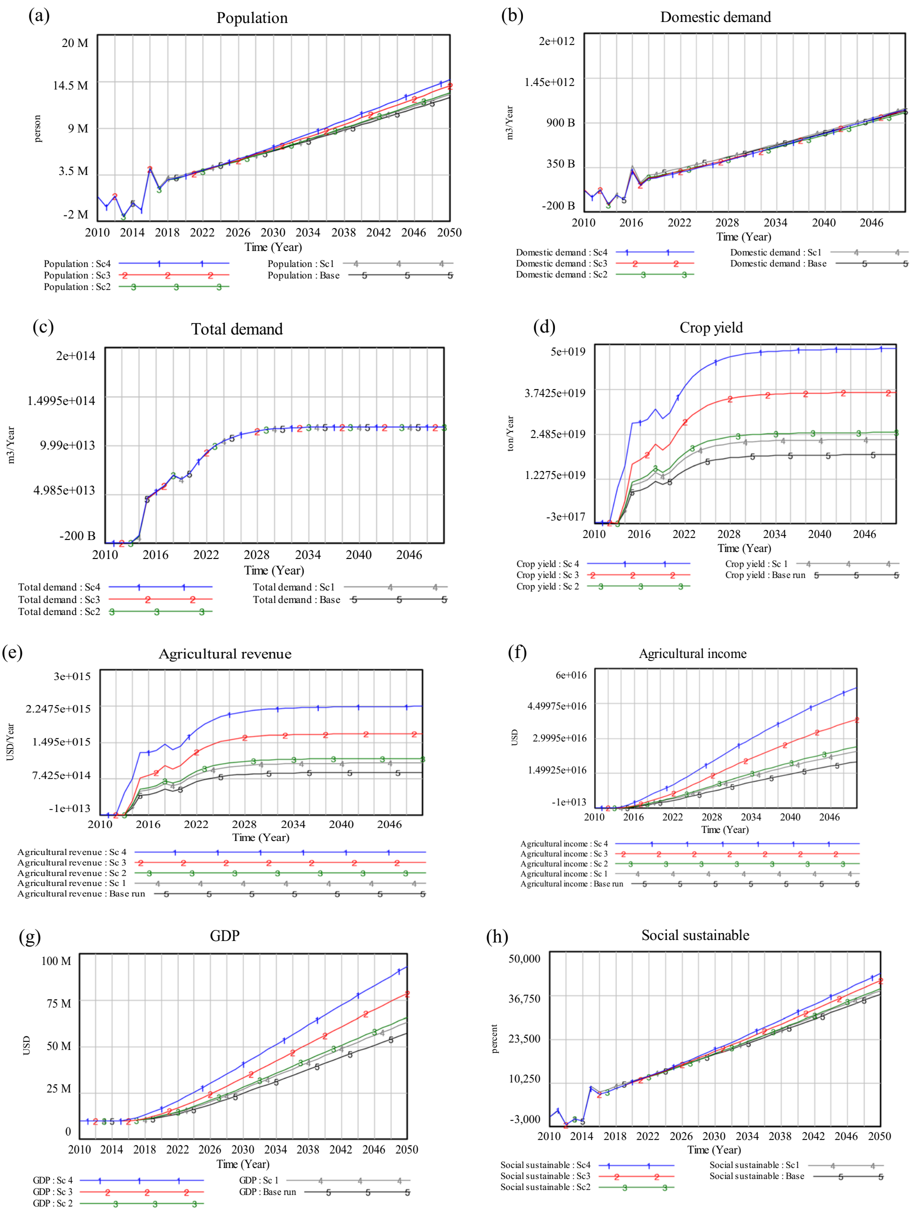

**Fig. 7** Behavior of social variables under five scenarios: (**a**) population, (**b**) domestic demand, (**c**) total demand, (**d**) crop yield, (**e**) agricultural revenue, (**f**) agricultural income, (**g**) GDP, (**h**) social sustainability. Source: findings of research

than the global per capita consumption (170 $m^3day^{-1}person^{-1}$) (Kermanshah Regional Water Authority 2020), reducing per capita water consumption was considered an important policy in water management. Per capita water consumption was assumed to be 215, 210, and 200 ($m^3day^{-1}person^{-1}$) in the second, third, and fourth scenarios, respectively. The findings indicate that the domestic water demand increases due to population growth even though the per capita water consumption decreases by about 30% (Fig. 7b and c).

Based on the results, the average annual rate of cultivation area change is 0.85%. The outcomes of the model's performance evaluation demonstrate that in order to avoid the decline in the harvest output of various commodities under normal conditions, it will be imperative to enhance the extraction of groundwater (Fig. 7d). Therefore, in baseline, the volume of groundwater will decrease more steeply, and in the horizon of 2050, its volume will be less than one million cubic meters (Fig. 6d).

Although the basin's population grew rapidly over the simulation period (Fig. 7a), the augmentation of water reserves in scenarios 3 and 4, along with improved irrigation efficiency, will establish an equilibrium between water supply and demand. This will result in a slower rate of growth for the total water demand in domestic and agricultural sectors (as depicted in Fig. 7c). Furthermore, it will also pave the way for speedy economic progress in the basin by 2050 (as indicated in Fig. 7e, f, and g). In this study, economic growth was modeled as a function of an increase in agricultural production, which is manifested in a rise in national income. There is evidence (e.g., Sertoglu et al. 2017; Tahamipour and Mahmoudi 2018) that agricultural production has a positive effect on GDP and economic growth. Based on Fig. 7g, the fourth scenario is the most effective scenario for economic purposes. Scenarios with any reduced rate in per capita water consumption have a negligible effect on the amount of total water demand, but scenarios with a higher irrigation efficiency and wastewater reuse in agriculture have an important impact on water supply and increasing crop yields. According to the results, the GDP will increase by about 50% in the third scenario and 80% in the fourth scenario during a 30-year time horizon. Fig. 7h shows the social sustainability index. Based on the results, the values of indicators such as social participation, social health, social responsibility, social trust, social security, and social solidarity were estimated to be 43.5%, 69.4%, 70.8%, 52.6%, 63.6%, and 74.4%, respectively. Based on Fig. 7h, the increasing trend of the social sustainability indexes indicates that the level of social indicators will improve and the social system of the study area will be accompanied by the growth of the quality of life in the future.

## 4 Discussion

This study developed an SD model to identify interaction feedback mechanisms between social and hydrological systems that are integrated into a complex socio-hydrology system. Based on the results, the decreasing trend in the volume of the dam indicates that the Gavshan dam will face significant challenges in supplying water for domestic and agricultural needs. It means that even with the highest efficiency in agriculture water consumption, there will not be enough water to meet the needs. This points out the necessity of balancing water supply or demand management strategies. Based on scenarios 3 and 4, using wastewater recycling can increase available water by about 30 $Mm^3$/year for agriculture. Furthermore, repairing the worn pipes of the water transmission network and reducing water leakage from 37% to 10% can save Kermanshah province from the water shortage for the domestic water supply. It is expected that with the increase in the cultivation area of agricultural products, according to the net irrigation requirement, the withdrawal from the resources will increase and as a result, the ability of the water resources system to respond to the growing demand will decrease (scenario 4). Irrigation of crops using recycled wastewater can be an economic policy when aiming to increase productivity. Jeong et al. (2020) affirmed that utilizing treated effluent for second-stage irrigation in nations or territories with elevated per capita domestic water usage can be a cost-effective approach for water administration. Mainardis et al. (2022) provided a comprehensive examination of the recycling of wastewater in agriculture. They recorded the difficulties of wastewater recycling, such as microbiological and public health effects, as well as the buildup of emerging pollutants in soils. As mentioned by Zamora-Ledezma et al. (2021), it is better to use modern technologies in wastewater recycling to reduce treated wastewater risks and prevent the entry of contaminants and heavy metals into the environment.

As demonstrated in scenario 4, better access to water and the reuse of wastewater have enhanced crop yields and Gross Domestic Product (GDP). The greater the crop yield and more intensified use of farmland, the higher the productivity and profitability of a farm. Thangiah et al. (2020) have stated that economic growth results in an increase in incomes, which motivates consumers to have more purchasing power, leading to an improved material quality of life and standard of living. Veisi et al. (2022) have also verified that factors like income and employment have a positive influence on the quality of life and the expansion of irrigated agriculture. Therefore, in addition to purchasing power and GDP growth, the quality of life indicator is influenced by the employment rate.

### 4.1 Limitation

This study will guide hybrid qualitative-quantitative modeling in domains of water management where multiple levels of dynamic interactions between social and hydrological systems are of significance. However, the study had several limitations. For example, due to the uncertainty in Iran’s inflation rate, this study could not deal with the inflation rate policy and prices of agricultural products in the scenarios. In this study, a variety of scenarios were simulated based on domestic water demand and agricultural water demand. As such, this study could not model the dynamics of the industry and environmental water demand.

## 5 Conclusions

This research conducted the applicability of a hybrid dynamic simulation model that would address human-water management issues and could promote agricultural development and social sustainability. The results indicate that the water resources system can not supply water to the growing population in the Gavshan watershed. Based on management scenarios, the effectiveness of leakage reduction strategies and wastewater reuse in recovering water resources and responding to population growth demand showed that wastewater reuse policies in agriculture can curb the water stress crisis. The hybrid SD model of this study relies on very precise relationships between human and water systems and has proposed new insights related to interactions among hydrological, agricultural, economic, and social components. Hybrid modeling could add value to socio-hydrology systems understanding, and as a consequence, would provide better policy scenarios. Based on the findings, it is advisable to construct a sewage treatment plant to sustain the volume of water resources and guarantee a steady supply of water for irrigation purposes in the times to come. In addition, it is suggested to avoid adverse consequences and prevent the entry of contaminants into the ecosystem using modern technologies in wastewater recycling. In this study, wastewater reuse was modeled as an economic and technical policy to curb the water crisis, and future studies can expand this model by considering environmental impacts. Furthermore, future research could extend the model of this study to the interpretability of wastewater reuse in agriculture and examine the socio-hydrological performance.

## Appendix

**Table 2** List of socio-hydrological modeling parameters for the Gavoshan watershed

| Model component | Equation | Variables and parameters | Type of variabe |
|---|---|---|---|
| Incoming flow | $F_{ine}(t) = F_{run-off}(t)+F_{return}(t) + F_{base}(t)$ | $F_{run\text{-}off}$; run-off flow | Auxiliary |
| | | $F_{return}$ (t); returns flow to the surface stream | Auxiliary |
| | | $F_{base}$ (t); base flow | Rate |
| Groundwater recharge | $R_{gr}(t) = V_{sur}(t)\times C_{gre}$ | $V_{sur}$ (t); surface flow volume | Stock |
| | | $C_{gre}$; groundwater recharge coefficient | Constant |
| Interbasin transfer flow | $F_{int}(t) = V_{sur}(t)\times C_{int}$ | $C_{int}$; outgoing interbasin transfer coefficient | Constant |
| Infiltration (I (t)) | $I(t) = Pre(t)\times C_{in}$ | Pre (t); precipitation | Auxiliary |
| | | $C_{in}$; coefficient of infiltration | Constant |
| Percolation (Per (t)) | $Pre(t) = C_{per} \times \left(V_{soil}(t) + F_{returngr}(t) - FC\right)$ | $C_{per}$; percolation coefficient | Constant |
| | | $V_{soil}$ (t); soil water | Stock |
| | | $F_{returngr}$ (t); returns flow to the groundwater | Auxiliary |
| | | FC; field capacity | Auxiliary |
| Crop yield (CRY (t)) | $CRY(t) = C_{cry}(t) \times Pro_{tion}(t) + I_{rr}(t)$ | $C_{cry}$ (t); coefficient of production | Constant |
| | | $Pro_{tion}$ (t); production | Exogenous |
| | | $I_{rr}$ (t); Irrigated area | Rate |
| Agricultural revenue (AR (p)) | $AR(p) = CRY(t) \times P_{cr}/Ex_{rate}$ | CRY (t); Crop yield | Auxiliary |
| | | $P_{cr}$; price of crops | Auxiliary |
| | | $Ex_{rate}$; exchange rate of IRR to USD | Auxiliary |
| Total water demand | $TWD = DWD(t) + AWD(t)$ | DWD (t); domestic water demand | Auxiliary |

**Table 2** (continued)

| Model component | Equation | Variables and parameters | Type of variabe |
|---|---|---|---|
| Social sustainability index (SSI) | $\mathrm{QOL, SH, SP, SR, SSE, SSO, ST} = 1/\mathrm{n}\sum_{\mathrm{i}=1}^{\mathrm{I}} \mathrm{I_i}$ | QOL; quality of life | Exogenous |
| | | SH; social health | Auxiliary |
| | | SP; social participation | Auxiliary |
| | | SR; social responsibility | Auxiliary |
| | | SSE; social security | Auxiliary |
| | | SSO; social solidarity | Auxiliary |
| | | ST; social trust | Auxiliary |
| Total social sustainability | $\mathrm{TSS} = \mathrm{QOL} + \mathrm{SH} + \mathrm{SP} + \mathrm{SR} + \mathrm{SSE} + \mathrm{SSO} + \mathrm{ST}$<br>$\mathrm{TSS} = \mathrm{QOL} + \mathrm{SH} + \mathrm{SP} + \mathrm{SR} + \mathrm{SSE} + \mathrm{SSO} + \mathrm{ST}$ | TSS; social sustainability | Stock |

Source: findings of research

**Acknowledgments** We sincerely thank all farmers and members of the Regional Water Company of Kermanshah who participated in the research interview.

**Data Availability** Data are available upon request.

## Declarations

**Ethical Approval** None.

**Consent to Participate** All authors contributed equally to the preparation of this manuscript.

**Consent to Publish** All authors have read the manuscript and agree to its publication.

**Disclosure of potential conflicts of interest** There is no conflict of interest.

**Research Involving Human Participants and/or Animals** None.

**Informed Consent** All authors have read the manuscript and agreed to its submission.

**Conflicts of Interest** The authors declare that they have no known competing financial interests or personal relationships that might be perceived to have influenced the research in this paper.

## References

Bano R, Khiadani M, Nyam YS (2022) System Archetypes Underlying Formal-Informal Urban Water Supply Dynamics. Water Resour Manage 36:4995–5010. https://doi.org/10.1007/s11269-022-03288-w

Behboudian M, Anamaghi S, Mahjouri N, Kerachian R (2023) Enhancing the resilience of ecosystem services under extreme events in socio-hydrological systems: a spatio-temporal analysis. J Clean Produc 397:136437. https://doi.org/10.1016/j.jclepro.2023.136437

Bo Y, Zhou F, Zhao J, Liu J, Liu J, Ciais P, Chang J, Chen L (2021) Additional surface-water deficit to meet global universal water accessibility by 2030. J Clean Produc 320:128829. https://doi.org/10.1016/j.jclepro.2021.128829

Conant B, Robinson CE, Hinton MJ, Russell HAJ (2019) A framework for conceptualizing groundwater-surface water interactions and identifying potential impacts on water quality, water quantity, and ecosystems. J Hydrolg 574:609–627. https://doi.org/10.1016/j.jhydrol.2019.04.050

Dong Q, Zhang X, Chen Y, Fang D (2019) Dynamic Management of a Water Resources-Socioeconomic-Environmental System Based on Feedbacks Using System Dynamics. Water Resour Manage. https://doi.org/10.1007/s11269-019-02233-8.

Elsawah S, Pierce SA, Hamilton SH, Hedwig van Delden HV, Haase D, Elmahdi A, Jakeman AJ (2017) An overview of the system dynamics process for integrated modelling of socio-ecological systems: Lessons on good modelling practice from five case studies. Environ Model Software 93:127–145

Food and Agriculture Organization (FAO) (2022) Chapter 4: Irrigation water needs. https://www.fao.org/3/s2022e/s2022e08.htm

Fatmawati K (2022) Gross domestic product: Financing and Investment Activities and State Expenditures. J Manajemen Organisa dan Industr 1:1

Jeong H, Bhattarai R, Adamowski J, Yu DJ (2020) Insights from socio-hydrological modeling to design sustainable wastewater reuse strategies for agriculture at the watershed scale. Agricul Water Manage 231:105983

Kellner E (2021) The controversial debate on the role of water reservoirs in reducing water scarcity. WIREs Water 8:3. https://doi.org/10.1002/wat2.1514

Kermanshah Agricultural Jihad Organization (2020) Statistics and information: Annual report. Kermanshah, Iran. http://kermanshah.maj.ir. (in Persian)

Kermanshah Meteorological Organization (2022) Meteorology data: Annual report. Kermanshah, Iran. http://www.kermanshahmet.ir/. (in Persian)

Kermanshah Regional Water Authority (2020) Management studies report on the operation and maintenance of diversion dam and irrigation and drainage network of Gavshan. Kermanshah, Iran. (in Persian)

Krejcie RV, Morgan DW (1970) Determining Sample Size for Research Activities. Educ Psycholo Measur 30:607–610. https://doi.org/10.1177/001316447003000308

Kurnianingtyas D, Santosa B, Siswanto N (2019) Structural and Behavioral Validity using a System Dynamic Simulation Approach: The Indonesian National Health Insurance System Problem. ICONIT 2019 - International Conference on Industrial Technology 36–45. https://www.scitepress.org/Papers/2019/94043/94043.pdf

Lähde E, Dahlberg N, Piirainen P, Rehunen A (2023) Ensuring Ecosystem Service Provision of Urban Water Nature-Based Solutions in Infill Areas: Comparing Green Factor for Districts and SWMM Modeling in Scenario Assessment. Environ Process 10:61. https://doi.org/10.1007/s40710-023-00676-1

Lin G, Palopoli M, Dadwal V (2020) From causal loop diagrams to system dynamics models in a data-rich ecosystem. In book: Leveraging Data Science for Global Heal 77–98. https://doi.org/10.1007/978-3-030-47994-7_6

Lindqvist AN, Fornell R, Prade T, Linda T, Sammar K, Birgit K (2021) Human-Water Dynamics and their Role for Seasonal Water Scarcity – a Case Study. Water Resour Manage 35:3043–3061. https://doi.org/10.1007/s11269-021-02819-1

Liu J, Liu Y, Wang X (2020) An environmental assessment model of construction and demolition waste based on system dynamics: a case study in Guangzhou. Environ Sci Pollut Res 27:37237–37259. https://doi.org/10.1007/s11356-019-07107-5

Luu T, Verhallen M, Duc Tran D, Sea WB, Binh Nguyen T, Quan Nguyen H (2022) Statistically examining the connection between dike development and human perceptions in the floodplains' socio-hydrology system of Vietnamese Mekong Delta. Sci Total Environ 810:152207

Mainardis M, Cecconet D, Moretti A, Callegari A, Goi D, Freguia S, Capodaglio AG (2022) Wastewater fertigation in agriculture: Issues and opportunities for improved water management and circular economy. Environ Pollu 296. https://doi.org/10.1016/j.envpol.2021.118755.

Massuel S, Riaux J, Molle F, Kuper M, Ogilvie A, Collard AL, Leduc C, Barreteau O (2018) Inspiring a Broader Socio-Hydrological Negotiation Approach with Interdisciplinary Field-Based Experience. Water Resour Res 54:4. https://doi.org/10.1002/2017WR021691

Melsen LA, Vos J, Boelens R (2018) What is the role of the model in socio-hydrology? Discussion of "Prediction in a socio-hydrological world." Hydrolog Sci J 63(9):1435–1443

Molajou A, Pouladi P, Afshar A (2021) Incorporating Social System into Water-Food-Energy Nexus. Water Resour Manage 35:4561–4580. https://doi.org/10.1007/s11269-021-02967-4

Mostert E (2018) An alternative approach for socio-hydrology: case study research. Hydrol Earth Syst Sci 22:317–329. https://doi.org/10.5194/hess-22-317-2018

Noutsopoulos C, Charalambous V, Koumaki E (2020) Evaluating the Fate of Emerging Contaminants in Wastewater Treatment Plants through Plant-Wide Mathematical Modelling. Environ Proce 7:1065–1094. https://doi.org/10.1007/s40710-020-00459-y

Penny G, Goddard JJ (2018) Resilience principles in socio-hydrology: A case-study review. Water Secur 4(5):37–43. https://doi.org/10.1016/j.wasec.2018.11.003

Popovic T, Kraslawski A, Barbosa-Póvoa A, Carvalho A (2017) Quantitative indicators for social sustainability assessment of society and product responsibility aspects in supply chains. J Int Stud 10(4):9–36. https://doi.org/10.14254/2071-8330.2017/10-4/1

Rahman MM, Penny G, Mondal MS, Zaman MH, Kryston A, Salehin M, Nahar Q, Islam MS, Bolster D, Tank JL, Müller MF (2019) Salinization in large river deltas: Drivers, impacts and socio-hydrological feedbacks. Water Secu 6:100024. https://doi.org/10.1016/j.wasec.2019.100024

Rebs T, Brandenburg M, Seuring S (2019) System dynamics modeling for sustainable supply chain management: A literature review and systems thinking approach. J Clean Produc 208:1265–1280. https://doi.org/10.1016/j.jclepro.2018.10.100

Sertoglu K, Ugural S, Bekun FV (2017) The Contribution of Agricultural Sector on Economic Growth of Nigeria. Int J Econo Finan Issue 7(1):547–552

Sriyono E, Budi Asri DP, Saedi S, Cameselle C (2021) Toward a social construction f water resources management: The case of Kalimantan. Civil Environ Engineer 8:1. https://doi.org/10.1080/23311916.2021.1999061

Statistical Center of Kermanshah (2020) Data and statistical information: Annual reports. Kermanshah, Iran. https://www.amar.mpo-ksh.ir. (in Persian)

Stosch KC, Quilliam RS, Bunnefeld N, Oliver DM (2022) Catchment-Scale Participatory Mapping Identifies Stakeholder Perceptions of Land and Water Management Conflicts. Land 11(2):300. https://doi.org/10.3390/land11020300

Sun Y, Liu N, Shang J, Zhang J (2017) Sustainable utilization of water resources in China: A system dynamics model. J Clean Produc 142:613–625

Tahamipour M, Mahmoudi M (2018) The role of agricultural sector productivity in economic growth: The case of iran's economic development plan. Res App Econo 10 (1):. https://doi.org/10.5296/rae.v10i1.12809.

Tehreem HS, Mk Ansar, Nassani AA, Moinuddin M, Abro Q, Zaman Kh (2020) Impact of average temperature, energy demand, sectoral value added, and population growth on water resource quality and mortality rate: it id time to stop waiting around. Environ Sci Pollut Res 27:37626–37644. https://doi.org/10.1007/s11356-020-09822-w

Thangiah G, Said MA, Majid HA, Reidpath D, Su TT (2020) Income Inequality in Quality of Life among Rural Communities in Malaysia: A Case for Immediate Policy Consideration. Int J Environ Res Publ Heal 24:17–23. https://doi.org/10.3390/ijerph17238731

Vanelli FM, Kobiyama M (2020) How can socio-hydrology contribute to natural disaster risk reduction? Hydrolog Sci J 65:S3

Veisi H, Deihimfard R, Shahmohammadi A, Hydarzadeh Y (2022) Application of the analytic hierarchy process (AHP) in amulti-criteria selection of agricultural irrigation systems. Agri Water Manage 267:107619

Xia J, Dong Y, Zou L (2022) Developing socio-hydrology: Research progress, opportunities and challenges. J Geograph Sci 32:2131–2146. https://doi.org/10.1007/s11442-022-2040-3

Xiang K, Li Y, Horton R, Feng H (2020) Similarity and difference of potential evapotranspiration and reference crop evapotranspiration – a review. Agri Water Manage 232:106043. https://doi.org/10.1016/j.agwat.2020.106043

Xu L, Gober P, Wheater HS, Kajikawa Y (2018) Reframing socio-hydrological research to include a social science perspective. J Hydrolo 563:76–83. https://doi.org/10.1016/j.jhydrol.2018.05.061

Zamora-Ledezma C, Negrete-Bolagay D, Figueroa F, Zamora-Ledezma E, Ni M, Alexis F, Guerrero VH (2021) Heavy metal water pollution: A fresh look about hazards, novel and conventional remediation methods. Environ Technol Innov 22:101504. https://doi.org/10.1016/j.eti.2021.101504

Zhou Y, Li X, Liu Y (2021) Cultivated land protection and rational use in China. Land Use Polic 106:105454. https://doi.org/10.1016/j.landusepol.2021.105454