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New hydro-economic system dynamics and agent-based modeling for sustainable urban groundwater management: A case study of Dehno, Yazd Province, Iran

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ABSTRACT

Water scarcity invariably poses a threat to the sustainability of cities and rural areas with limited resources, especially in developing countries. This paper presents a new hydro-economic model based on system dynamics and agent-based simulation to enhance the sustainability of urban groundwater. Dynamic pricing was performed based on several parameters, such as resource conditions, price elasticity, consumption history and climate change, to improve the sustainability of groundwater and cover the costs of implementing strategies. Different scenarios based on pricing, rationing, culturalizing, and non-revenue water control strategies were applied in the village of Dehno in Yazd Province as the case study with an arid climate. The results showed that several scenarios can achieve the goal, but, in drought conditions, only a combination of all the strategies will work.

1. Introduction

Growing human activities, rapid socio-economic development and drought conditions have caused changes in water-related environmental issues, such as long-term shortage of water resources, rapid deterioration of water quality, scarcity, and degeneration of aquatic ecosystems. These changes are detrimental to the coordinated management of water systems for sustainable urban and rural areas (Cui, Chen, Xue, Li, & Zeng, 2019; Echeverría, 2020). In recent years, most Middle Eastern countries have experienced a growing scarcity of freshwater resources. This scarcity, along with pollution, calls for a change in water policies and a better focus on the society's preferences in connection with the use of water and development, thus to ensure the availability and sustainable management of water and sanitation for all (SDG6). Water management, as it is nowadays, does not adequately tend to modify the existing policies, derive the necessary directives, or bring water issues under long-term planning (Ho, Alonso, Forio, Vanclooster, & Goethals, 2020). Changing the focus of water management approaches from supply to demand can improve water conservation and sustainability. In this respect, specific adaptive management policies are needed for a transition towards groundwater sustainability. Sustainability in this sense would refer to the exploitation of water resources for the present needs while maintaining them for future generations without adverse environmental, economic and social consequences (Yusuf et al., 2020). Achieving this goal entails pricing, public awareness, culturalization, technical tools, water recycling and sewage systems (Hof, Blázquez-Salom, & Garau, 2018). Hydro-economic solutions can serve as promising tools for the more efficient management of water resources (Alamanos, Latinopoulos, Papaioannou, & Mylopoulos, 2019). Scarcity pricing is an effective strategy to reduce demand while simultaneously generating additional revenues (Sahin, Siems, Stewart, & Porter, 2016). Setting low water prices leads to water wastage and is considered as an ineffective policy in a water management system. (Mercadier & Brenner, 2020). There are several methods to solve the complexity of water management, hydro-economic modeling, and inclusion of complex parameters such as feedback, interdependence and emergence (Guerrero, Schwarz, & Slinger, 2016). Using an agent-based or system dynamics model is an example of such methods. In an agent-based model, the behavior of the system emerges bottom-up from the interactions of individuals with one another and with their environment based on a set of pre-specified rules. A system dynamics model, however, represents the behavioral pattern of the system based on generalizable underlying structures whose main elements are endogenous feedback and accumulation of quantities over time. Unlike the agent-based method, a system dynamics model is

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usually presented at an aggregate level (i.e., with a top-down structure) and has broader boundaries (Morshed, Kasman, Heuberger, Hammond, & Hovmand, 2019).

A lot of research has been done in the fields of hydro-economics and water pricing for sustainable urban water management. Tortajada, González-Gómez, Biswas, and Buurman (2019) reviewed water demand management strategies for water-scarce cities in Spain. The result showed that education, awareness raising for water conservation and promotion of water-saving technologies have major impacts on sustainable water consumption. Babamiri, Pishvaee, and Mirzamohammadi (2020) conducted a financial analysis of sustainable management strategies of urban water distribution networks under an increasing block tariff structure with a system dynamics approach. Rojas, Garcia-Vega, and Herrera-Torres (2019) explored economic policies and their role as a tool for managing the sustainability of water resources. Lopez-Nicolas, Pulido-Velazquez, Rougé, Harou, and Escriva-Bou (2018) showed the best urban water-saving solution based on economic solutions. Molinos-Senante and Donoso (2016) examined the impact of water tariffs on drought conditions for sustainable urban water management. They showed that hydro-economic modeling improves water use sustainability. Fan (2019) explored hydro-economic models of sustainable water resource management. Sahin et al. (2016) offered several methods to control demand, such as pricing in drought conditions. They also advocated hydro-economic models to protect urban water during droughts (Sahin, Bertone, Beal, & Stewart, 2018). Massarutto (2020) reviewed the theoretical and applied literature in the field of residential water economic models. He provided many examples of approaches and solutions that are more consistent with the sustainability theory. Mercadier and Brenner (2020) analyzed tariff sustainability in Buenos Aires water and sanitation concessions amidst economic instability. Water scarcity exerts a significant influence on price elasticity and sustainable cities. If water scarcity is severe, household responsiveness to prices decreases, though this effect is attenuated in environmentally concerned communities (Garrone, Grilli, & Marzano, 2019). Favre and Montginoul (2018) reviewed hydro-economic models in Tunisia for the sustainability of cities and showed the cost-recovery principle strongly depends highly on high-consumption households. The affordability principle was found to only concern piped households. The averaging-out principle does not indicate the local scarcity value of water. Al-Saidi (2017) reviewed urban water economic models for sustainable consumption in Yemen. He compared increasing block tariffs with other pricing schemes.

Due to the excessive extraction of groundwater for intense agricultural activities, Yazd plain, a water-scarce district in the center of Iran, has been faced with a serious water crisis during the past decade. This is more or less like the conditions in the other regions of Iran. Appropriate pricing can have a positive effect on water consumption in Iran. In some past research works, the extent of this effect is calculated. Through a systematic review and meta-analysis, Shadivand, SAYEH, and ASKARI (2019) investigated the factors affecting the price and income elasticity of household water demand in Iran. Using Rosenthal and Robin's approach in the systematic review, the effects of price and income elasticities were calculated for household water demand. Then, based on the heterogeneity of the calculated effects, random and fixed models were used to combine the results. Rezaee and Shojaa (2020) estimated the income and the price elasticity of Kermanshah urban water demand. Price elasticity indicates a negative correlation between price changes and water demand. If the price of water increases by 10 %, the demand for it will decrease by 4.3 %. Abolhasani, Tajabadi, and Shahnoushi Forushahi (2018) reviewed 21 empirical case studies in Iran from which 65 estimates of price elasticity for residual water demand were collected. The inclusion of income, use of time-series datasets, natural logarithm function of demand and application of the stone-gray theory were all found to affect the estimate of price elasticity. The population density and the use of OLS techniques to estimate the demand parameters did not significantly influence the estimate of price elasticity.

To implement a hydro-economic model of urban water management, practical straightforward measures, effective incentives, and fines should be taken into consideration. This makes water consumption optimal (Sharifi, 2020). For example, the inclusion of a subscriber's consumption history in pricing may create an incentive for saving, or an exponential increase in prices as a fine may be a deterrent for those who consume a lot. Paying attention to these points complements the research work of others. For urban water sustainability management, this study proposes a model with hydro-economic considerations in social and individual dimensions. The price dimension includes cost, supply-demand balance, resource conditions (i.e., the sustainability of groundwater), and rainfall. The bill, which represents the households section of water pricing, is calculated based on consumption pattern, history, price elasticity, and comparison with others. This case study was planned to focus on the sustainability of urban groundwater. It was due to its special circumstances that the village of Dehno in the province of Yazd was selected for the study. The area has a dry climate and is beset with an extended drought. The purpose of the study is not to determine the price-demand or elasticity function; rather, water pricing is considered as a tool to control consumption in favor of groundwater sustainability. It also covers the costs of the proposed strategies.

As indicated in Fig. 1, the study was carried out through a number of steps. After the problem was identified, an area was selected for a case study. Once the possible solutions were reviewed for the problem, a hypothesis was extracted. The problem was modeled through system dynamics and agent-based methods. The pricing formula, taxes, duties and incentives were calculated too. The results of the model simulation were consistent with the past real behavior of households, and the structure was successfully evaluated through a test. Then, different scenarios of demand management were tested to select the best one that could maintain the sustainability of water resources in drought conditions, meet the costs of the water supply company, and cause the least dissatisfaction.

The rest of this paper is organized into several parts. The second part presents the methodology of the study. In the third part, the results of strategy implementation are offered, and the fourth part discusses those results. Finally, the fifth part ends the paper with the conclusion.

2. Methodology

2.1. Case study

Dehno is a rural area in the province of Yazd, Iran, with a population of about 5000 in 1000 families. The area has arid climatic conditions with low rainfall and high evaporation. It is located far from seas (500 km to the Persian Gulf and 700 km to the Caspian Sea) and in the vicinity of a vast desert with low relative humidity and high temperature (Fig. 2).

Dehno has been selected for a case study for several reasons:

a) The area has an arid climate. Recently, it has suffered from drought, and precipitation has decreased significantly. Prolonged drought and increased demand for water have led to an uncontrolled increase in water abstraction from wells. This has caused a significant reduction in groundwater resources.

b) The village is located at the distance of 10 km from Yazd, but it seems connected to Yazd due to the enlargement of the city. Its climate is the same as that in Yazd. The demand for water has increased significantly due to the population growth, the expansion of the water supply network, and the occurrence of drought. Therefore, the volume of groundwater has significantly reduced. Based on the opinions of the experts at ABFA Company, if this trend continues for less than eight years, the resources will dry up. In recent years, as Piezo metrics suggest, the groundwater in Yazd-Ardakan aquifers has gone down due to drought and excessive consumption, and the role of rainfall has become greater than before (Fig. 3). These conditions are true about Dehno too; the demand for water has increased, and the volume of groundwater has

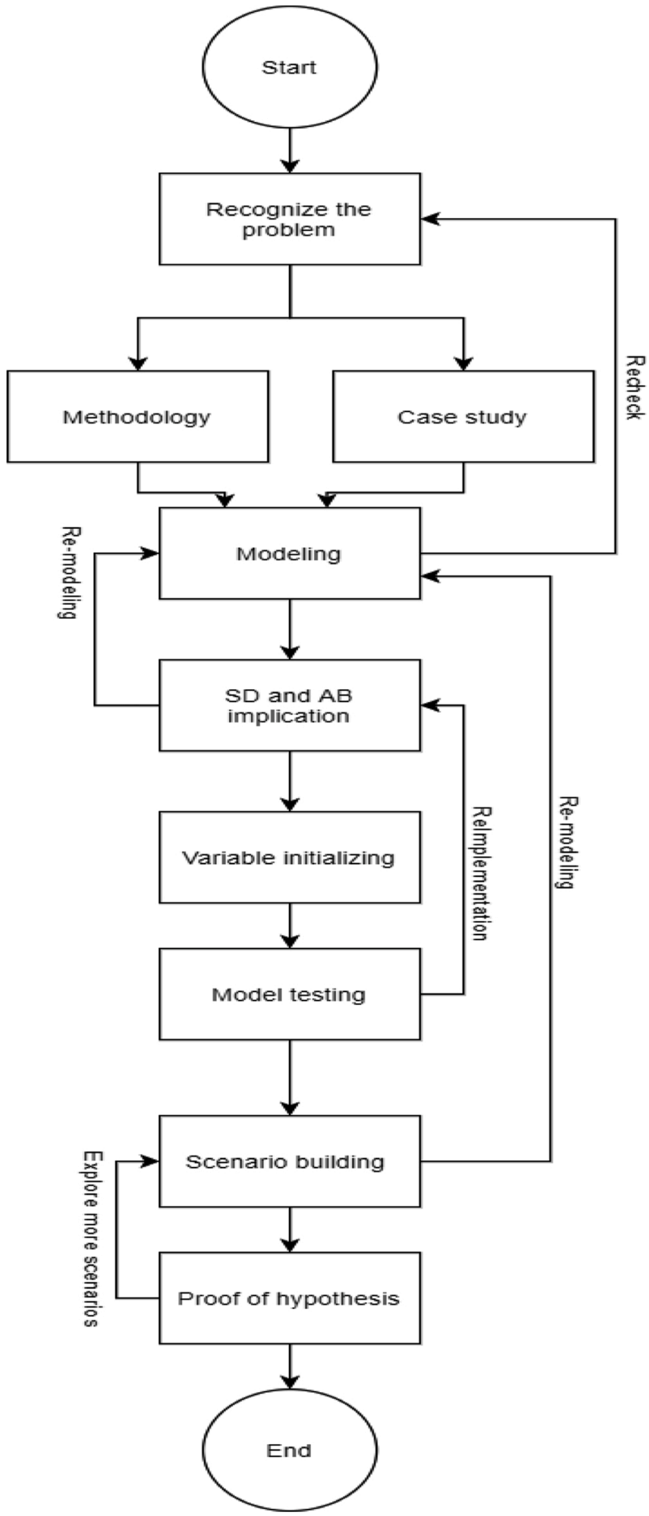


Fig. 1. The steps of the study.

decreased (Fig. 4).

c) The region has more than 30 wells that supply Dehno and Yazd drinking networks. Therefore, water management in the region is very important for ABFA.

d) The main sources of water in the region are groundwater and the water transferred from Isfahan Province. Fig. 5 addresses the supply of water from these sources. As it turns out, the majority of consumption is for groundwater.

e) The garden houses are located among the agricultural lands

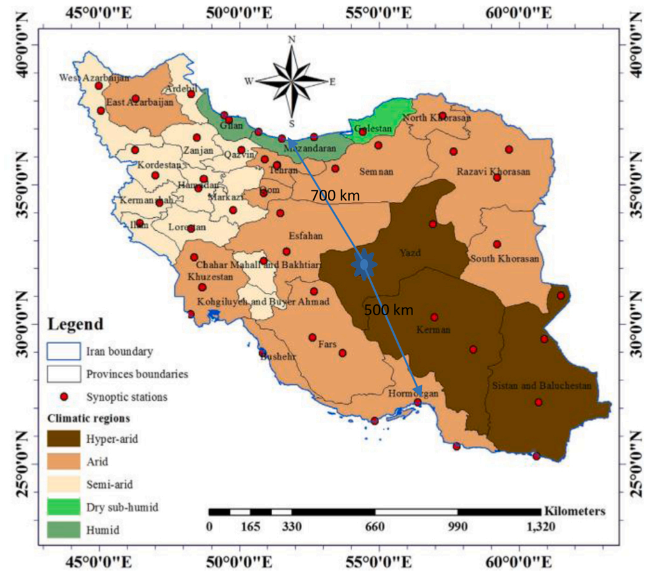


Fig. 2. Climate zones in the Iranian provinces (Karandish, Hoekstra, & Hogeboom, 2020).

(Fig. 6) and have used urban water to irrigate plants. In the recent drought, agricultural water resources have dried up. This has led to a large increase in consumption and a critical situation in drinking water resources. Fig. 7 compares the average consumption values in Yazd and Dehno from 2009 to 2019. The average consumption per person has increased in Dehno but decreased in Yazd. Due to the low price of domestic water in the village, households have also used it for agriculture in drought conditions.

All the figures and the tables about the case study area were obtained from ABFA, Yazd Water Resources Company, and expert opinions in this company.

2.2. Hypothesis

Before the study was launched, it was hypothesized that a combination of demand management and pricing policies would maintain the sustainability of groundwater resources in drought conditions in Dehno, Yazd.

2.3. Modeling

Water management involves a complex system of different factors and behaviors that influence one another. To model such a system, first, the main variables were extracted through a review of the literature and (Arasteh & Farjami, 2021). Then, the relationships among the variables were identified based on a causal-loop diagram, which is one of the best tools to determine the types of relationships among system variables. Fig. 8 shows a causal loop diagram of six main loops in hydro-economic modeling, including consumption, price change, revenue, population, supply, and waste loops. All the loops were corrective. Price-related loops were extracted to determine the extent of the hydro-economic impact on the other factors.

1. Price-> bill-> income-> culture-> consumption and waste-> supply-demand balance-> price.
2. Price-> bill-> satisfying-> theft-> consumption and waste-> supply-demand balance
3. Price-> bill-> satisfying-> theft-> income-> culture-> consumption and waste-> supply-demand balance-> price

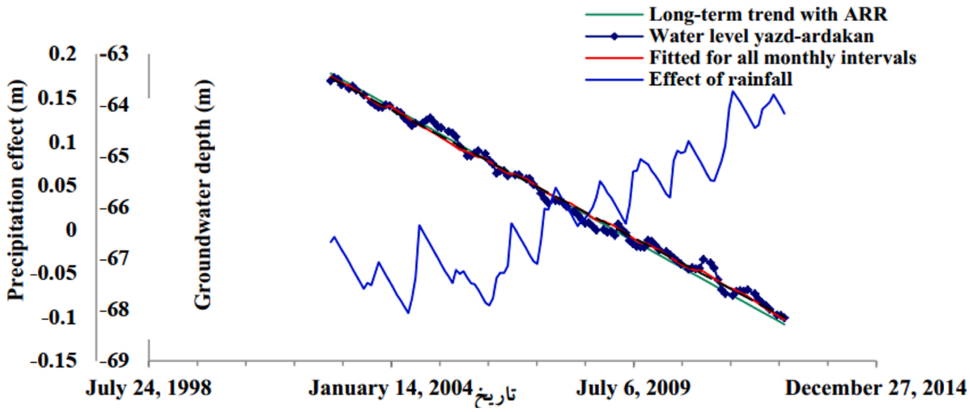


Fig. 3. Conditions of the groundwater resources in the Yazd-Ardakan plain: Piezo metric level of the aquifer and the effect of precipitation on it from 1998 to 2014 (Barzegari, 2018).

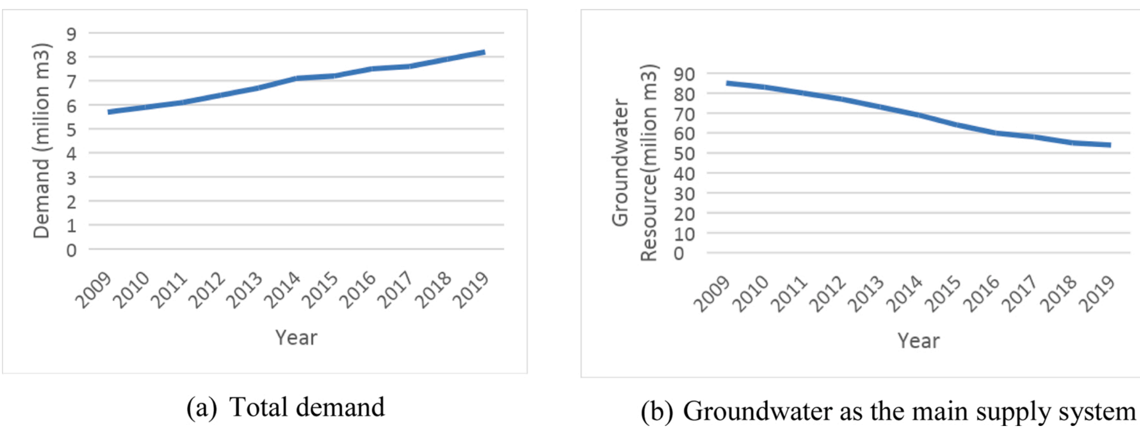


Fig. 4. Demand, groundwater capacity, and average consumption in Dehno from 2009 to 2019.

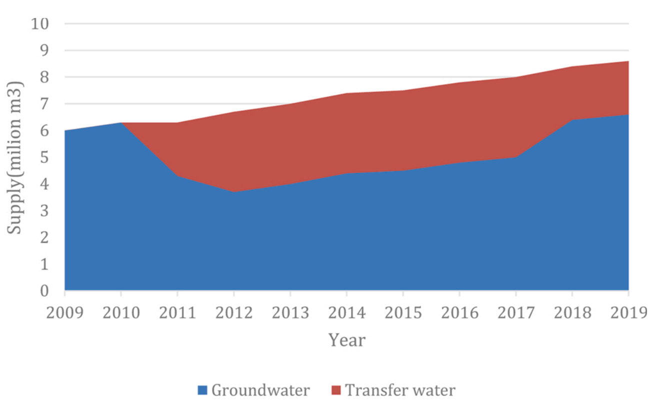


Fig. 5. The amount of water supply over ten years from 2009 to 2019 and the percentages of the water supplied by two main resources.

4 Price-> bill-> satisfying-> theft-> income-> waste and wastewater network reform-> consumption and waste-> supply-demand balance-> price

In the next step, it was necessary to determine the main variables and the sub-variables based on the reference model. Table 1 shows the main variables of the system. The simulation column specifies which variable belongs to the simulation method. The formula column shows the method of calculation.

Due to the complexity and interactivity of the factors, a combination of system dynamics and agent-based methods was used to model the system behavior. The system dynamics method is a top-down one and can be applied to high-aggregation cases (i.e., high-abstraction cases). It assumes that all processes are continuous and makes use of multiple feedback mechanisms, delays, and complex non-linear processes described by differential equations. On the other hand, the agent-based methods use a bottom-up perspective, deal with discrete processes, and handle middle-to-low aggregation (i.e., low abstraction). A value proposition of agent-based modeling tools is the ability to capture the dynamics at work between the multiple autonomous agents and the heterogeneous groups of agents interacting in a system (Wilensky & Rand, 2015). In Fig. 9, the simulation environment can be seen as a part of the system dynamics with a stock and flow diagram. The stocks include reservoirs, groundwater, surface water, households, dynamic price, profit, culture, waste, and theft percentage. The Anylogic v8.05 software was used to model the dynamics of the agents, namely the households in the agent-based section and the stock and flow diagram in the system dynamics section. The model was divided into the following subsystems which interacted with one another:

Water supply subsystem: This subsystem includes a groundwater, surface water, and sewage treatment network. The water conservation sector must adopt control policies to protect water resources. For example, surface water volume equals the sum of rainwater and river water minus overflow, soil infiltration and surface evaporation. The green area in Fig. 9 shows this subsystem.

Demand and balance subsystem: The purpose of this subsystem is to balance the supply and demand in the drinking water network. The yellow area in Fig. 9 shows this subsystem.

People are the agents of the system. Fig. 10 shows the households that are part of the demand system. With a click on each household, its

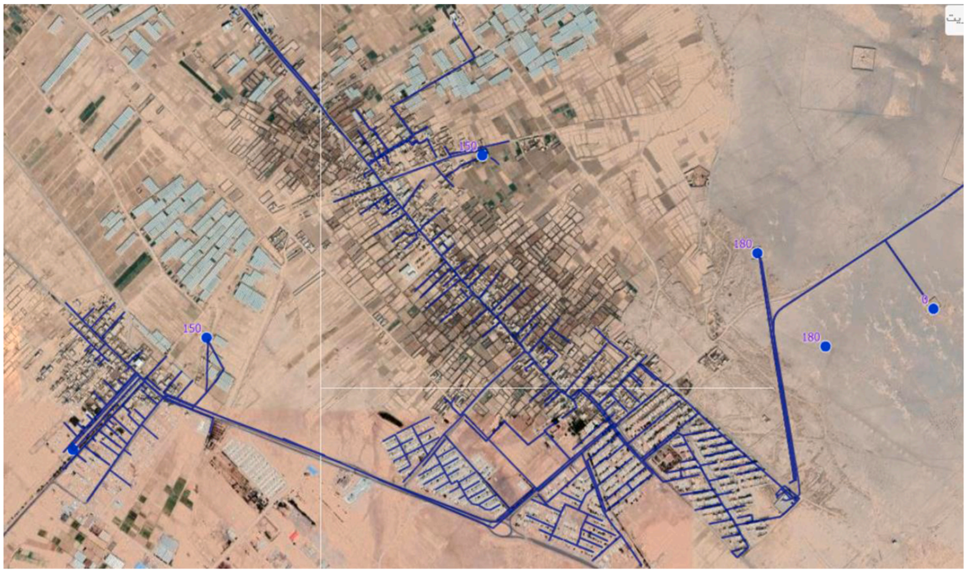


Fig. 6. Dehno drinking water network and wells: The households are among the agricultural lands.

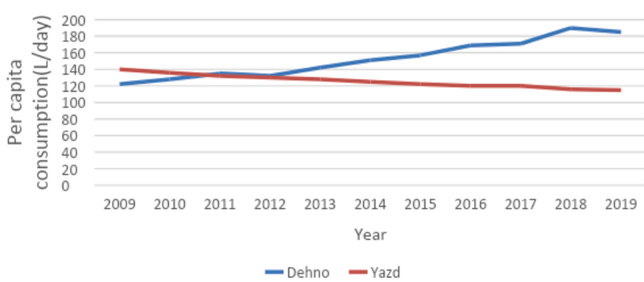


Fig. 7. Per capita domestic water consumption in Yazd vs Dehno in ten years.

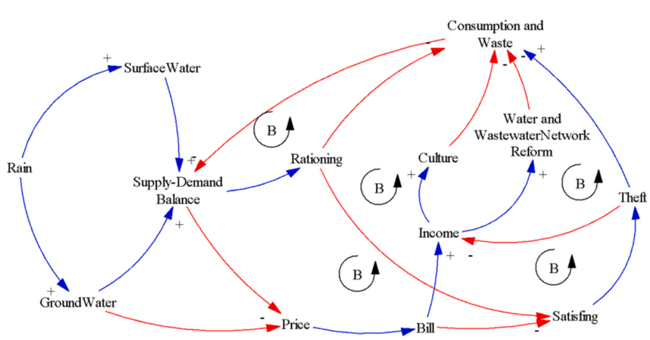


Fig. 8. The causal loop diagram of the model.

specifications and the amount of its consumption are displayed on a new page. Each household is characterized in terms of age, gender, number of members, income, consumption, bill, the possibility of theft or consumption without a meter, and satisfaction.

NRW control subsystem: Non-revenue water (NRW) is the water produced but lost before it reaches the customer. Losses can be real losses (through leaks, sometimes referred to as physical losses) or apparent losses (through theft or metering inaccuracies). High levels of NRW are detrimental both to the financial viability of water utilities and to the quality of water itself. NRW is typically measured as the volume of the water lost, which is a part of the net water produced (AL-Washali, Elkhider, Sharma, & Kennedy, 2020; Torkaman, Ahmadi, & Aminnejad, 2021). This subsystem reduces water loss and increases consumption through developing a distribution network. Therefore, network development should be cautious concerning resource capacity. It should also regard waste reduction, household monitoring, and wastewater reuse. The treated wastewater contributes to the supply of water to farmlands and non-drinking usages. The subsystem is shown in the maroon area of Fig. 9.

Awareness subsystem: It serves to raise households' awareness and create incentives for proper consumption. The blue area in Fig. 9 shows this subsystem.

Cost and revenue subsystem: The purpose is for cost recovery through dynamic pricing. To determine costs and revenue, a stock is considered as the profit, and the monthly costs including the cost of awareness, smart meter, network modification, and monitoring are deducted from it. The revenues come from operations, bills, grants, and government budgets. Consequently, the costs can be applied based on the existing profit, which forms a dynamic cycle. A rise in the price increases the revenue and offsets some of the company's costs. The company spends part of its revenue on household awareness, network refinement, optimization of water use, and balancing the supply and demand in the long run. The red area in Fig. 9 shows this subsystem.

The dynamic pricing function is part of this subsystem. Proper and fair water pricing has two advantages. It saves water and gives incentives to save. It also pays off NRW control and cultural costs. In pricing, justice should be ranked first. Second, household incentives or savings should be taken into account. Third, there should be excessive consumption fines. In this study, water pricing is done in the dimensions of price and bills. The price is based on water balance, resource sustainability, climate change, rationing, inflation, and management factors. If there is an overflow, certain incentives are provided for consumption in agriculture and industry. This part of the price algorithm is calculated based on system dynamics. The price is the same for all the households and is calculated in each period (i.e. per month).

$$\mathrm{Price}_t = \int \frac{d}{dt}\left((\mathrm{ManagePrice} + \mathrm{ActualCost})*\frac{\mathrm{Balance}_t}{\mathrm{Balance}_{t-1}}*\frac{\mathrm{GroundWater}_t}{\mathrm{GroundWater}_{t-1}}*\frac{\mathrm{Rainfall}_t}{\mathrm{Rainfall}_{t-12}}*\frac{\mathrm{Rationing}_t}{\mathrm{Rationing}_{t-1}}\right)*\mathit{ManageRatio}*\mathit{BasePrice} \tag{1}$$

Table 1
The main variables of the system and their types and formula.

Variable	Variable type	Method	Formula
Groundwater In	Flow	System Dynamics	Delay (Rain, Effect Time) * Groundwater Effective Area *delay (Supply * Return Percent, Effect Time) +delay (Surface water Penetration * Surface water Penetration Percent, Effect Time)
Groundwater	Stock	System Dynamics	Groundwater in – Groundwater out
Groundwater Out	Flow	System Dynamics	Limit (0, Groundwater Debit, Min (Groundwater, Reservoir))
Surface water In	Flow	System Dynamics	Flowing water + River
Surface water	Stock	System Dynamics	Surface water in – Surface-water Out - Evaporation – Surface-water Penetration – Surface-water Overflow
Reservoir input	Flow	System Dynamics	Surface water Out + Groundwater Out + Transition Water
Reservoir output	Flow	System Dynamics	Limit (0, limit Max ((Demand)*(1-Rationing/100), Household s. Household s Real Consume () +Waste), Reservoir)
Reservoir	Stock	System Dynamics	Reservoir Input – Reservoir Output – Reservoir Overflow
Income	Flow	System Dynamics	Sum of Bills
profit	Stock	System Dynamics	Income Cost
Costs	Flow	System Dynamics	(Monitor and Correct + Awareness) *people
NRW percentage	Stock	System Dynamics	Waste in-waste out
Culture	Stock	System Dynamics	Culture increase-Culture decrease
Rainfall	Variable	System Dynamics	$\sum_{t-12}^{t} Rain$
Demand	Variable	System Dynamics	Waste + consumer Demand
Bills	Variable	Agent-based	$\sum_{i}^{i=consumers.count\ ()} Consumers.ConsumersBill\ ()$
Consumer demand	variable	Agent-based	$\sum_{i}^{i=consumers.count\ ()} Consumers.ConsumersNeed\ ()$
Theft	Variable	Agent-based	$\sum_{i}^{i=consumers.count\ ()} Consumers.Teft\ ()$

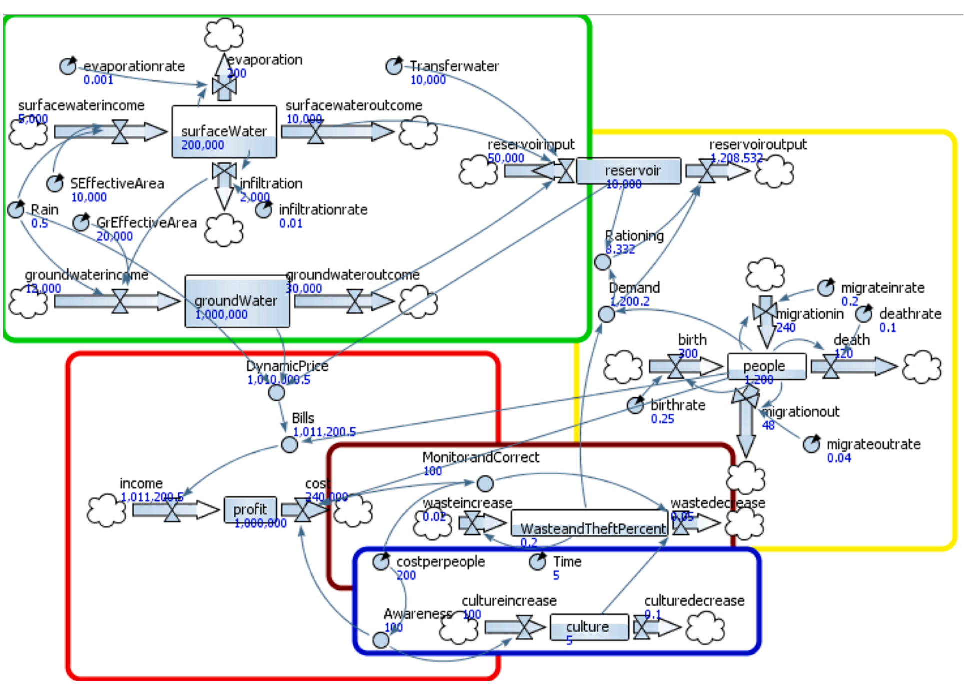


Fig. 9. Main stock and flow diagram in the Anylogic software.

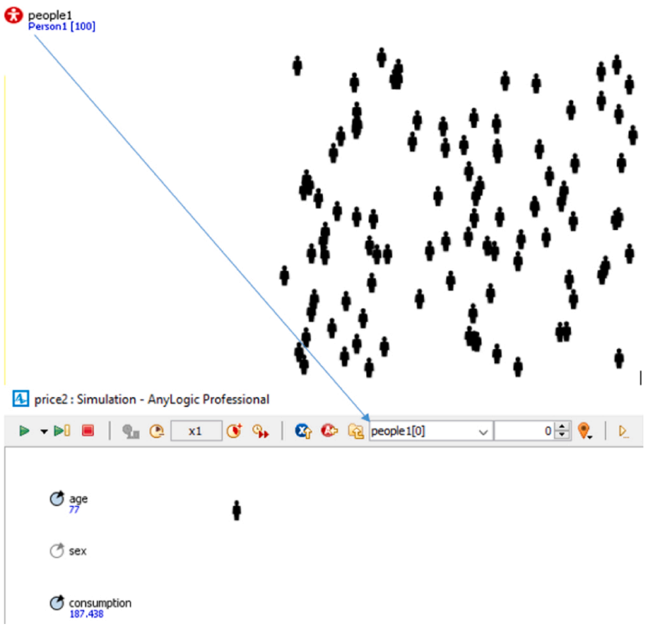


Fig. 10. The agent-based section of the simulation.

$$\text{If } (\text{Surface water overflow}_t > 5000 \,||\, \text{Reservoir OverFlow}_t > 5000), \text{ then price}_t * = 0.8 \quad (2)$$

It is necessary to simulate each household to calculate the bill. Therefore, agent-based simulation is used rather than system dynamics.

Table 2
Dynamic pricing variables.

Variable/Idiom	Description
consume_t	The volume of household consumption in the current month
Base price	The base price of water announced by the government
Fixed price	The price of water if it is fixed or changes manually
Dynamic price	The price of water if changed automatically base on the price formula in every month and different in every household
Price_t	Price in the current month
Price elasticity	There was elasticity in the drinking water price. The households were divided into three levels: 1 Low volume users (poor level): -0.10 to -0.30 2 Medium volume users (middle level): -0.4 to -0.5 3 High water users (rich level): -0.7 to -0.8
Bill	Consumption bill in the current month
Manager's price	Price changes based on the manager's opinion
Actual cost	The primary cost of services
$\frac{\textbf{Balance}_t}{\textbf{Balance}_{t-1}}$	Changes in balance (demand-supply balance ratio in the current month compared to the previous month)
$\frac{\textbf{Groundwater}_t}{\textbf{Groundwater}_{t-1}}$	Changes in the volume of groundwater resources (the conditions of groundwater resources compared to the previous month)
$\frac{\textbf{Rainfall}_t}{\textbf{Rainfall}_{t-12}}$	Climate change (current rainfall compared to the previous year)
$\frac{\textbf{Rationing}_t}{\textbf{Rationing}_{t-1}}$	Dietary changes (ratio of rationing in the current month to the previous month)
DamOverFlow_t	Overflow in the surface water
TankOverFlow_t	Overflow in the reservoir
$\frac{\textbf{consume}_t}{\textbf{consume}_{t-12}}$	Household consumption changes (current consumption over the same month in the previous year)
$\frac{\textbf{consume}_t * \textbf{consumers.count}}{\sum_1^{\text{consumers.count}} \textbf{consume}}$	Ratio of the household consumption to the average consumption in the region
Manager's ratio	The management determines the coefficient. It guarantees the implementation of executive costs. It is determined in such a way that the amount of revenue of the company is not significantly different from that in the fixed pricing method

$$\text{Bill} = \int \frac{d}{dt} \frac{\text{consume}_t}{\text{consume}_{t-12}} * \frac{\text{consume}_t * \text{consumers.count}}{\sum\limits_{1}^{\text{consumers.count}} \text{consume}} * \text{Price}_t * \text{PriceElastic} * \text{consume}_t \quad (3)$$

Price elasticity must be involved too. Water is inelastic for essential usages such as drinking, food preparation and sanitation (Price elasticity for this usage is between -0.30 and -0.10), but it is elastic for such tasks as recreational sports and non-essential usages like irrigation and washing. In this study, the results of several other studies including Abolhasani et al. (2018), Karimlou, Hassani, Mehrabadi, and Nazari (2019), Rezaee and Shojaa (2020), Shadivand et al. (2019) and Tajabadi, Abolhassani, and Shahnoushi (2018) were used to calculate the Price Elasticity. It is considered as a variable based on household income. The amount of household income was calculated with regard to the household size and the amount of household consumption. Accordingly, households and price elasticity were divided into three levels. Based on the findings, an increase in the price had an opposite effect on the consumption. Also, the increase in the price had the greatest impact on the middle class.

Table 2 shows the details of the pricing method and the calculation of the household bills. The variable column introduces the influential factors in the pricing formula, and the description column gives definitions and interpretations for the variables.

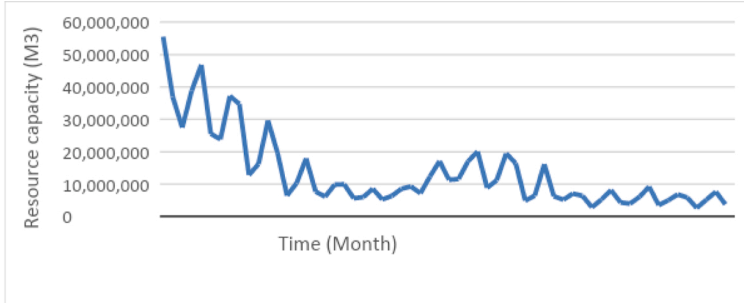
3. Results

3.1. Model validation

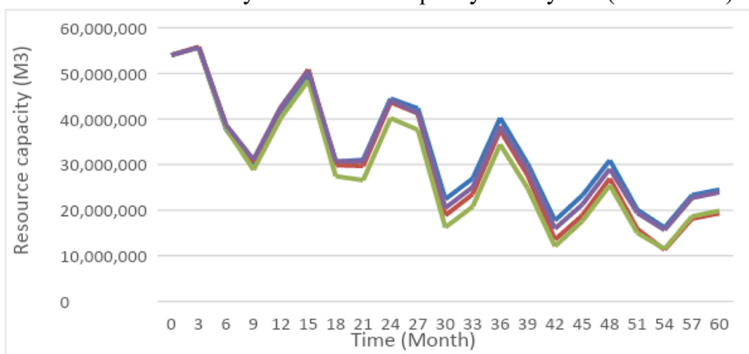
A model can simulate the behavior of a system reliably only if the designer includes his real needs in it (Homer & Oliva, 2001). There are different evaluation and validation methods to compare simulated and actual data (Barlas, 1996), including the tests introduced by Forrester and Barlas (Legasto, Forrester, & Lyneis, 1980; Sweeney & Sterman, 2000). The time was divided into two periods, from 2018 to 2019 for a two-year evaluation and comparison with the past and from 2019 to 2025 for a five-year simulation. There are three tests to evaluate the model as follows:

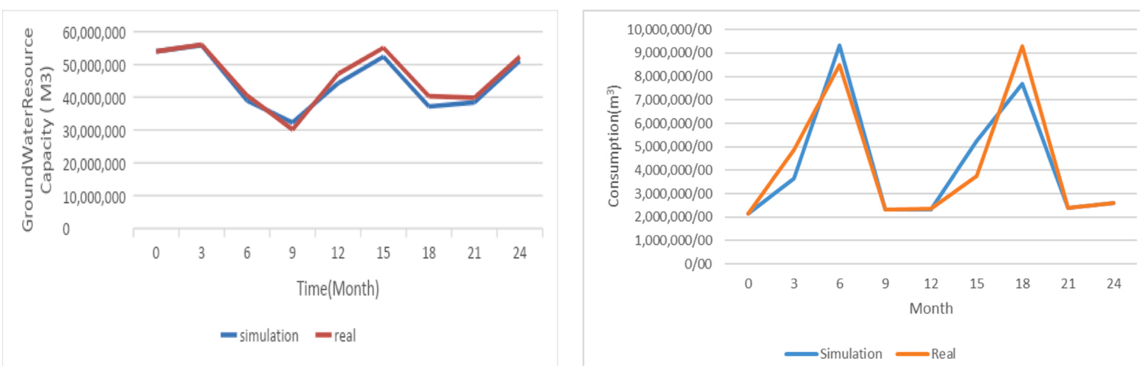
a. Structure validation: The model is run over a long period (15 years). According to Fig. 11a, the structure is relatively stable, but, with the continuation of the current trend from month 144 (in the year 2033), the groundwater resources will be in a critical state.

b. Repetition of the behavior: The model is run several times to evaluate its behavior (Fig. 11b). Slight changes indicate the uncertainty of the model. However, they still follow the same structure.



a. Structure analysis: Resource capacity in 15 years (2021-2036)





c. Simulation vs. reality: The capacity of groundwater and households consumption (2019-2021)

Fig. 11. Model validation.

c. Comparison with the past: The model is compared to the real system behavior in the two years before the simulation (from 2019 to 2021). As shown in Fig. 11c, the model simulation matches the past. This test serves to calibrate the water demand function with the real data. The real data are based on the consumption of the households and the annual report of ABFA resource status in the case study during the two-year period before the simulation.

The factors that affect the amount of consumption include the change of water prices, prevention of unauthorized use, proper consumption culture, and forcible reduction of consumption through rationing. To determine the best method in drought conditions, it is necessary to set a series of scenarios, make reviews, and compare the simulation results. To find the best solution, a combination of different strategies has been examined and finally implemented in 19 different scenario in three aspects including initial scenarios, drought conditions and strategies comparisons. A comparison of the conditions of resources in these scenarios with the current conditions continuing during the five years of simulation is shown in Fig. 12, and Table 4 reviews all the scenarios with cost/income details. In every scenario with a fixed price change, the price increases to a certain extent every month, and this change is the same for everyone. In dynamic pricing, however, the price change is based on the proposed formula, calculated separately for each household. Based on the formulation, if the consumption increases, the price will increase exponentially; a fine has been predicted in the pricing formula. Also, if the household consumption is low, the price will be reduced to zero.

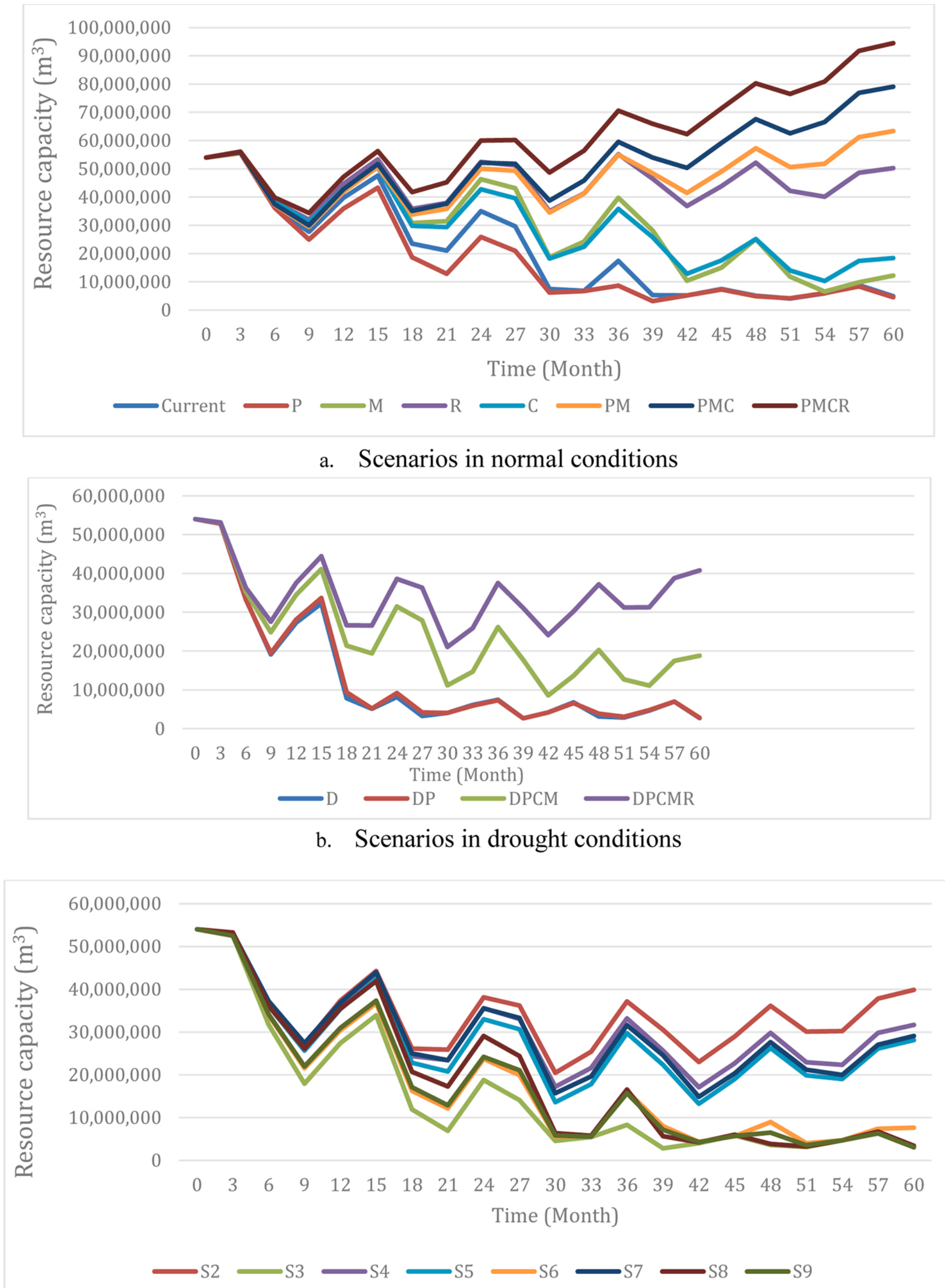
3.2. Initial scenarios

a. The current conditions

Resource capacity indicates the groundwater resources sustainability index as the main goal of this paper. The sustainability of groundwater resources will be disrupted if the capacity of water resources is less than 20 million cubic meters. In the current trend, Dehno will face problems and crises from the 30_{th} month onwards.

b. Static pricing: a fixed increase in the price every month

In this scenario, the price of water should be increased just slightly each month so as not to put pressure on households. Therefore, this scenario is very useful for financing the current expenses and increasing the company's revenues, but it does not lead to reduced consumption and, thus, to the sustainability of water resources. Its failure to reduce consumption is due to paying no attention to fines and incentives; as a result, it cannot change the behavior of subscribers. According to the ABFA consumption data, when water prices increased, consumption reduced in four months, but it then returned to its original state. According to ABFA experts, this may be due to the low price increase and



a. Scenarios in normal conditions

b. Scenarios in drought conditions

c. Scenarios with a combination of the main strategies (pricing, rationing, NRW control, culturing)

Fig. 12. Resources Sustainability in the examined scenarios for 60 months (2021-2026).

lack of price elasticity considerations.

c. NRW control and households monitoring

This includes monitoring the households, controlling the network against theft, fixing the old networks, repairing breakdowns rapidly, and reducing the network loss. In this regard, household monitoring means to prevent the manipulation of metering devices and network theft. This requires the use of technology and power and is not possible without investment. According to the ABFA experts, with such monitoring, the rate of consumption is reduced by 2% each month for one year and the budget required in each month is 50 million Rials. This budget must be offset by pricing. In this scenario, pricing is based on fixed and periodic (monthly) increases (SP scenario).

d. Rationing and limiting the consumption with smart meters

In this scenario, water consumption is controlled using smart meters. The service provider controls these meters remotely. Each family is assigned a daily allowance based on the number of members and the history of consumption. If the consumption reaches the threshold, the automatic meter is cut off and only a small amount of water passes through it. The cost of this task must be offset by pricing. In this scenario, pricing is based on fixed and periodic (monthly) increases (as in the SP scenario). The cost of a smart meter for each household is 10 million Rials, and the number of replacements per month is determined based on the company's revenue.

e. Awareness and Culture

This scenario has to do with the awareness-raising, educating and informing of the households about the conditions of water resources and how to conserve them. According to the experts at the local water supply company, this task costs 50 thousand Rials per household per month and the savings in each month is 2%, but the results are not measurable in the long run. The cost must be offset by pricing, which, in this scenario, is based on fixed and monthly increases (as in the SP scenario)

f. Dynamic pricing + NRW control

In this section, scenario M is implemented with dynamic pricing, which is the method of pricing proposed in this study. The average price change in dynamic pricing is the same as fixed price change, but the revenue is almost doubled. This is because the income is accrued through fines and exponential bill change on high-consumption households.

g. Dynamic pricing + NRW control + Awareness

In this scenario, a combination of the previous scenarios is used along with awareness. According to the experts at the service-providing company, promoting the culture and education of households requires less NRW control, so the investment is dedicated to them.

h. Dynamic pricing + NRW control + Awareness + Rationing

Dynamic pricing serves to cover the inevitable costs by combining NRW control, culture and rationing. This method has the best efficiency to balance the consumption and the sustainability of water resources, but the main problem is that it requires more investment than the other methods. The needed funds must be offset either by high prices, through government assistance, or in a smart manner over time. But what is needed for culture building if rationing is done? To answer this question, the following points can be considered:

- Dieting leads to implicit dissatisfaction. Whether this dissatisfaction is expressed with protests or remains mentally (da Silva Monte & Morais, 2019).
- Because water is not supplied as much as it can be, it may lead to unauthorized removal of the meter or tampering with it, which, in turn, leads to further incidents.
- Customers' awareness about the drought situation helps to raise their acceptance of measures such as water rationing and dynamic pricing. Awareness can be a great help to satisfaction and non-disruption (Michel, 2017).

Based on Fig. 12a, the best scenario is the one with a minimal loss (i. e., minimal network leakage, breakdown, accident and theft). In such a program, the demand is equated with the supply (i.e., a case of equilibrium) as much as possible. The best scenario is PMCR, or dynamic pricing with NRW control, household awareness and water rationing. The last four scenarios contribute to resource sustainability, but their performance during a drought needs to be examined.

3.3. Drought conditions

Since the study area is subject to droughts and is currently in that condition, different hydro-economic scenarios should be examined in four conditions as follows:

1 Sustainability in drought conditions

Drought in this study is defined as a 50 % reduction in precipitation. In this case, as shown in Fig. 12b, from the 18_{th} month, i.e., from the second half of 2019, the underground resource capacity would be less than 20 million cubic meters and the region would be in crisis. Therefore, consumption management policies would have to be applied.

2 Drought condition + Dynamic pricing

If pricing is applied only as a demand management tool, it will not work in a crisis and the goal of the study, which is underground resource sustainability, cannot be met. Therefore, other policies need to be applied with the revenue from new ways of pricing.

3 Drought condition + Dynamic pricing + Awareness + NRW control (DPCM)

If consumption control policies, including pricing, awareness and monitoring of the network and households, are applied in a drought crisis, the conditions will improve a lot, but the region will still be in the crisis from the 30_{th} month and in hot seasons. Therefore, rationing policies need to be applied too.

4 Drought condition + Dynamic pricing + Awareness + NRW control + Rationing (DPCMR)

This refers to the simultaneous application of consumption control policies and rations. Using smart control meters, the consumption of all the subscribers can be reduced by 20 %. As a result, the maximum allowed consumption is 80 %. In addition, network monitoring and theft prevention, promotion of households' education and culture, dynamic pricing, and implementation of incentives and fines should also be taken into account when a crisis occurs. As shown in Fig. 12b, in the present state of affairs, the resources are not in crisis and have some stability.

The question that arises is how to apply consumption control policies (namely pricing, rationing, monitoring and culture) at the time of crisis. Also, since practicing these policies is costly, the policies must be managed by the controlling of the cost. For this purpose, different combinations of the proposed scenarios have been tested to determine the best one.

3.4. Comparison of the strategies

As shown in Fig. 12b, the best scenario is the combination of pricing, rationing, NRW controlling and culturing. The cost of control and awareness raising comes from the revenue of dynamic pricing. High prices and rationing may cause social discontent, so they should be practiced cautiously. To solve this problem, a combination of strategies (e.g., pricing, rationing, NRW control and culturing), as presented in Table 3, proves to be the best selection. Since the cost of control is high, it cannot be implemented at a low price; therefore, the first case (i.e., the moderate price increase with senior NRW control) has been eliminated. S1 is not operationally feasible because pricing cannot cover the costs. Based on Fig. 12c, the best scenario is S2 when the price change takes place at a medium level through rationing. Also, the control of theft and wastewater can be done with just a little culture-building. Table 4 presents a detailed review of the scenarios.

4. Discussion

According to the results gained from the scenarios and based on Fig. 12 and Table 4, there are certain points worth discussing.

- The increase of price alone in the long term has little effect on the sustainability of water resources. If combined with proper rationing, however, it yields better results. If prices rise too much or rations become too tight, local resources are widely used, which decreases the infiltration of shallow local aquifers into deep drinking water aquifers. This strategy reduces the resources for a long time, increases the network theft, and reduces the bill payment power.
- According to ABFA experts, low rations do not reduce consumption because the same amount of water is consumed when the households are connected to the network. Therefore, rationing should be done with the help of smart meters, and the water withdrawal of every

Table 3
Comparison of the main strategies (i.e., pricing, rationing, NRW control and culturing).

	Price = low Rationing = high	Price = mid Rationing = mid	Price = high Rationing = low
NRW control = high, Culturing = low	S1	S2	S3
NRW control = mid, Culturing = mid	S4	S5	S6
NRW control = low, Culturing = high	S7	S8	S9

Table 4
Review of the scenarios.

	Drought	Static pricing (Rial/ M^3 in Month)	Dynamic pricing (Rial/ M^3 Month)	Waste control (Million Rials/Month)	Culture (Thousand Rial/ household in Month)	Rationing (percent)	Income (Million Rial/Month)	Sustainability	Sustainability In drought
Current status	No	No	No	No	No	No	0	No	No
Static price change	No	50	No	No	No	No	5	No	No
NRW control	No	50	No	50	No	No	0	No	No
Rationing	No	50	No	No	No	20	0	Yes	No
Awareness	No	50	No	No	500	No	0	No	No
Dynamic pricing + NRW control	No	No	50	50	No	No	5	Yes	No
Dynamic pricing + NRW control + Awareness	No	No	50	50	50	No	5	Yes	No
Dynamic pricing + NRW control + Awareness + Rationing	No	No	50	50	50	20	0	Yes	No
Drought condition	Yes	No	No	No	No	No	0	No	No
Drought condition + Dynamic pricing	Yes	No	50	No	No	No	10	No	No
Drought condition + Dynamic pricing + Awareness + NRW control	Yes	No	50	No	50	20	0	No	No
Drought condition + Dynamic pricing + Awareness + NRW control + Rationing	Yes	No	50	50	50	20	−5	Yes	Yes
S2	Yes	No	70	50	50	20	0	Yes	Yes
S3	Yes	No	95	100	20	10	30	No	No
S4	Yes	No	35	50	50	30	−5	Yes	Yes
S5	Yes	No	70	50	50	20	5	Yes	Yes
S6	Yes	No	95	50	50	10	35	No	No
S7	Yes	No	35	30	100	30	−10	Yes	Yes
S8	Yes	No	70	30	100	20	10	No	No
S9	Yes	No	95	30	100	10	30	No	No

household should be limited and specific so that it cannot use more than specified. Also, it induces the idea of water shortage, which may result in the saving of water.

- Static pricing does not help to reduce consumption, nor does it make a great difference from the current conditions. It is because price elasticity is not applied, the households become accustomed to the constant rise of prices, and they do not change their consumption. Besides, a steady rise in prices may not reflect drought or wet conditions. Dynamic pricing can solve these problems; the price increases more when the resource stability is at risk, the supply-demand balance is disturbed, or dryness occurs. Likewise, the price will decrease if the conditions reverse or there is a significant increase in the volume of overflow resources.
- When the revenue generated by rising prices is devoted to awareness raising and NRW control, the change in resource sustainability is quite noticeable. This change has been accounted for in the proposed scenarios, and it has also been reported in the studies of ABFA experts.
- In a drought condition, if the cost of awareness raising is low or zero, there are only focuses on NRW control and rise of prices, delayed consumption savings will occur, and resource volume diagrams will be initially zeroed and then corrected. This type of change can be seen in scenarios S2 and S3.
- As the DPCM scenario suggests, one can expect the sustainability of water resources even in drought conditions without rationing. However, even in these circumstances, limited rations are suggested. It both helps the sustainability of the resources and encourages the idea that resources are limited and running out. This, in turn, promotes the culture of consumption.
- As the results suggest, economic scenarios cannot be efficient without considering the culture and NRW control factors; every action within a scenario entails the constant practice of culture and control.
- S2, S4, S5, and S7 are the top resource sustainability scenarios. Tight rationing and rising prices, although sustaining the resources, will lead to widespread public discontent, which will have long-term consequences. There is no possibility of implementation if the scenarios have negative profits (i.e., the costs are more than the income). As a result, S7 and S4 scenarios are also set aside, and S2 and S5 are recommended. These two scenarios contribute to the sustainability of resources and the maintenance of the relative balance of supply and demand.

Using the proposed method has a series of advantages and challenges as follows:

Advantages

- Appropriate method: Each household bill is calculated based on its consumption history, income, and property size.
- Effectiveness: The proposed method has a significant positive effect on the reduction of consumption.
- Comprehensiveness: Different factors, including specific conditions, regions and water resources, are considered in this method.
- Consumption and tax incentives: When water resources are felt to be adequate, there are incentives for consumption. When there are severe resource constraints, the taxes and duties imposed on the consumption increase exponentially; thus, the price increases exponentially.

Challenges

- Computational complexity: Due to the use of different strategies, calculations are complex, and it is unfortunately difficult for the household to understand.
- Severe sensitivity: Changes in consumption, supply-demand balance, and resource situation make the prices change suddenly.

Policy implications

Based on the empirical results, certain notes on policymaking can be presented as follows:

- Rationing not only helps to reduce consumption but also induces the idea of water shortage, which is a kind of culture-building task. Therefore, in crisis, it is recommended to cut off the drinking water network with prior notice at certain times of the day
- One of the most important problems in the region is the use of drinking water in agriculture, which is due to the drought crisis. Giving awareness of the water conditions and the imposition of fines on high-consumption households can be effective strategies. As it was observed in the studied region, in the short run, awareness-raising had the greatest effect on the reduction of consumption. On average, the consumption was reduced by 2% in each monthly period.
- It is recommended to replace the current district meters with smart meters. The advantages of these meters are consumption flow control, consumption control, average consumption control per day, and setting the maximum permissible use.
- Since agricultural uses are part of the domestic uses, it is interesting to consider water recycling and the reuse of greywater for irrigation rather than fresh water. Water reuse is quite easy to implement and of the least cost; it results in considerable savings.
- Water demand for irrigation is much more elastic to changes in water price. So, water tariffs and monitoring are essential in this area to accomplish sustainable exploitation.

5. Conclusion

Water allocation depends on exogenous development drivers, economic benefits, and the society's perception of water preferences (Dalcin & Fernandes Marques, 2020). Hydro-economic models can serve as valuable tools for the better understanding of water allocation systems as well as the improvement of decision-making and water resources management (Alamanos et al., 2019). System dynamics and agent-based modeling are also powerful tools for resource simulation and integrated water resource management (Amadei, 2020). This study was conducted to test certain hydro-economic strategies of managing the drinking water demand in the village of Dehno in Yazd Province, Iran. The area has experienced long-term drought and suffered from water shortage. To enhance the sustainability of groundwater resources in that area under drought conditions, different scenarios were examined. Dynamic water pricing formulas were presented and implemented by system dynamics and agent-based simulation. As prescribed by this pricing system, each household's bill is calculated based on the amount of consumption, consumption pattern, price elasticity and dynamic price. The dynamic price of water is the same for everyone, but rainfall, rationing and resource volume affect it.

As a result, both water economy and consumer awareness should be considered in water pricing. The scenarios that were performed in this regard were able to meet the goal of the research, which was to achieve the sustainability of groundwater resources. The best scenario in drought conditions was a combination of medium dynamic price increase, control the consumption with rations and smart meters, and NRW control through network modification and household monitoring.

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.

References

Abolhasani, L., Tajabadi, M., & Shahnoushi Forushahi, N. (2018). *Price elasticity of residential water demand: A Meta analysis of studies on water demand,(case study: Iran)*.

Alamanos, A., Latinopoulos, D., Papaioannou, G., & Mylopoulos, N. (2019). Integrated hydro-economic modeling for sustainable water resources management in data-scarce areas: The case of lake Karla watershed in Greece. *Water Resources Management, 33*(8), 2775–2790.

Al-Saidi, M. (2017). Urban water pricing in Yemen: A comparison of increasing block tariffs to other pricing schemes. *Water International, 42*(3), 308–323.

AL-Washali, T. M., Elkhider, M. E., Sharma, S. K., & Kennedy, M. D. (2020). A review of nonrevenue water assessment software tools. *Wiley Interdisciplinary Reviews Water, 7*(2), e1413.

Amadei, B. (2020). Agent-based and system dynamics modeling of water field services. *Challenges, 11*(2), 13.

Arasteh, Mohammad Ali, & Farjami, Yaghoub (2021). Supporting Sustainable Rural Groundwater Demand Management with Fuzzy Decision Analysis: A Case Study in Iran. *Utilities Policy, 70*, 101215. https://doi.org/10.1016/j.jup.2021.101215

Babamiri, A. S., Pishvaee, M. S., & Mirzamohammadi, S. (2020). The analysis of financially sustainable management strategies of urban water distribution network under increasing block tariff structure: A system dynamics approach. *Sustainable Cities and Society, 60*, Article 102193.

Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics. *System Dynamics Review, 12*(3), 183–210.

Barzegari, F. (2018). Prediction of aquifer fluctuations using neural networks models and HARTT model (Case study: Yazd-ardakan plain). *Iranian Journal of Watershed Management Science and Engineering, 12*(42), 102–111.

Cui, D., Chen, X., Xue, Y., Li, R., & Zeng, W. (2019). An integrated approach to investigate the relationship of coupling coordination between social economy and water environment on urban scale-A case study of Kunming. *Journal of Environmental Management, 234*, 189–199.

da Silva Monte, M. B., & Morais, D. C. (2019). A decision model for identifying and solving problems in an urban water supply system. *Water Resources Management, 33*(14), 4835–4848.

Dalcin, A. P., & Fernandes Marques, G. (2020). Integrating water management instruments to reconcile a hydro-economic water allocation strategy with other water preferences. *Water Resources Research, 56*(5). e2019WR025558.

Echeverría, J. M. A. (2020). Cross-country evidence for social dimensions of urban water consumption during droughts. *Journal of Cleaner Production*, Article 120895.

Fan, Y. (2019). *Water price regulation model establishment &Influences on urban water resource in Harbin, China*. Atlantis Press.

Favre, M., & Montginoul, M. (2018). Water pricing in Tunisia: Can an original rate structure achieve multiple objectives? *Utilities Policy, 55*, 209–223.

Garrone, P., Grilli, L., & Marzano, R. (2019). Price elasticity of water demand considering scarcity and attitudes. *Utilities Policy, 59*, Article 100927.

Guerrero, C., Schwarz, P., & Slinger, J. H. (2016). *A recent overview of the integration of System Dynamics and Agent-based Modelling and Simulation*.

Ho, L., Alonso, A., Forio, M. A. E., Vanclooster, M., & Goethals, P. L. (2020). Water research in support of the Sustainable Development Goal 6: A case study in Belgium. *Journal of Cleaner Production*, Article 124082.

Hof, A., Blázquez-Salom, M., & Garau, J. M. (2018). Domestic urban water rate structure and water prices in Mallorca, Balearic Islands. *Boletín de la Asociación de Geógrafos Españoles, 77*, 52–79.

Homer, J., & Oliva, R. (2001). Maps and models in system dynamics: A response to Coyle. *System Dynamics Review, 17*(4), 347–355.

Karandish, F., Hoekstra, A. Y., & Hogeboom, R. J. (2020). Reducing food waste and changing cropping patterns to reduce water consumption and pollution in cereal production in Iran. *Journal of Hydrology, 586*, Article 124881.

Karimlou, K., Hassani, N., Mehrabadi, A. R., & Nazari, M. R. (2019). Calculating Price elasticity of water demand using gene expression programming based on economic, social and meteorological variables. *Water Resources Management, 33*(12), 4171–4188.

Legasto, A., Forrester, J. W., & Lyneis, J. M. (1980). *System dynamics*. North Holland.

Lopez-Nicolas, A., Pulido-Velazquez, M., Rougé, C., Harou, J. J., & Escriva-Bou, A. (2018). Design and assessment of an efficient and equitable dynamic urban water tariff. *Application to the city of Valencia, Spain. Environmental modelling & software, 101*, 137–145.

Massarutto, A. (2020). Servant of too many masters: Residential water pricing and the challenge of sustainability. *Utilities Policy, 63*, Article 101018.

Mercadier, A. C., & Brenner, F. S. (2020). Tariff (un) sustainability in contexts of price (in) stability: The case of the Buenos Aires water and sanitation concession. *Utilities Policy, 63*, Article 101005.

Michel, D. (2017). Iran's impending water crisis. *Water, Security and US Foreign Policy*, 168.

Molinos-Senante, M., & Donoso, G. (2016). Water scarcity and affordability in urban water pricing: A case study of Chile. *Utilities Policy, 43*, 107–116.

Morshed, A. B., Kasman, M., Heuberger, B., Hammond, R. A., & Hovmand, P. S. (2019). A systematic review of system dynamics and agent-based obesity models: Evaluating obesity as part of the global syndemic. *Obesity Reviews, 20*, 161–178.

Rezaee, H., & Shojaa, S. (2020). Estimation of income and price elasticity of kermanshah drinking water demand. *Journal of Water and Sustainable Development, 7*(3), 13–24.

Rojas, H. R. G. G., Garcia-Vega, D., & Herrera-Torres, H. A. (2019). *Water policy in* (pp. 137–152). Mexico: Springer.

Sahin, O., Bertone, E., Beal, C., & Stewart, R. A. (2018). Evaluating a novel tiered scarcity adjusted water budget and pricing structure using a holistic systems modelling approach. *Journal of Environmental Management, 215*, 79–90.

Sahin, O., Siems, R. S., Stewart, R. A., & Porter, M. G. (2016). Paradigm shift to enhanced water supply planning through augmented grids, scarcity pricing and adaptive factory water: A system dynamics approach. *Environmental Modelling & Software, 75*, 348–361.

Shadivand, M., SAYEH, M. A., & ASKARI, H. (2019). *Investigating the effective factors on price and income elasticity for household water demand in Iran: A systematic review and meta-analysis*.

Sharifi, A. (2020). Trade-offs and conflicts between urban climate change mitigation and adaptation measures: A literature review. *Journal of Cleaner Production*, Article 122813.

Sweeney, L. B., & Sterman, J. D. (2000). Bathtub dynamics: Initial results of a systems thinking inventory. *System Dynamics Review, 16*(4), 249–286.

Tajabadi, M., Abolhassani, L., & Shahnoushi, N. (2018). Meta-analysis of price elasticity for urban domestic water consumption in Iran. *Journal of Water and Wastewater/Ab va Fazilab, 29*(1).

Torkaman, N., Ahmadi, H., & Aminnejad, B. (2021). Calibration of the continuous water model based on the NRW patterns. *Journal of Applied Water Engineering and Research*, 1–9.

Tortajada, C., González-Gómez, F., Biswas, A. K., & Buurman, J. (2019). Water demand management strategies for water-scarce cities: The case of Spain. *Sustainable Cities and Society, 45*, 649–656.

Wilensky, U., & Rand, W. (2015). *An introduction to agent-based modeling: Modeling natural, social, and engineered complex systems with NetLogo*. Mit Press.

Yusuf, A., Sodiq, A., Giwa, A., Eke, J., Pikuda, O., De Luca, G., Di Salvo, J. L., & Chakraborty, S. (2020). A review of emerging trends in membrane science and technology for sustainable water treatment. *Journal of Cleaner Production*, Article 121867.