

Assessing the impacts of groundwater management policies on farmer cooperation using agent-based modeling

Sayed-Ali OHAB-YAZDI¹, Azadeh AHMADI (✉)²

1 Department of Civil Engineering, Isfahan University of Technology, Isfahan 8415683111, Iran.

2 Faculty of Civil, Water and Environmental Engineering, Shahid Beheshti University, Tehran 1983969411, Iran.

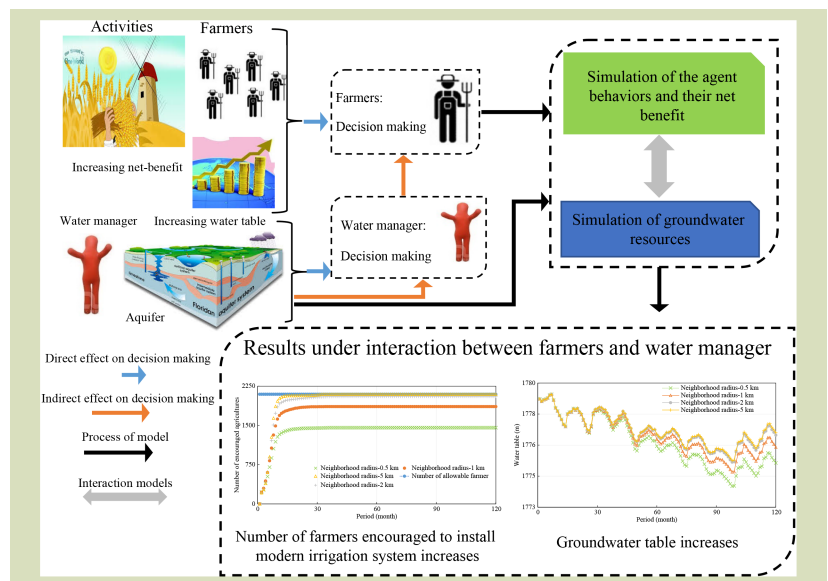
KEYWORDS

Agent-based modeling, *AnyLogic*, farmers' cooperation, behavioral subsystem, system dynamics, groundwater depletion

HIGHLIGHTS

- A coupled human-natural model based on an agent-based model was developed.
- Different levels of farmer cooperation on region sustainability were evaluated.
- Different scenarios based on farmer characteristics and behavior were developed.
- Penalties for overexploitation of groundwater resources increased cooperation.
- Awareness raising and training can increase 600 of users of modern irrigation systems.

GRAPHICAL ABSTRACT



Received December 22, 2023;

Accepted August 23, 2024.

Correspondence: az_ahmadi@sbu.ac.ir

ABSTRACT

This study presents a new holistic framework for modeling farmer decision-making by integrating both top-down and bottom-up approaches. It uses three interlinked subsystems to evaluate how changes in water policies impact farmer decisions and profits: the first model simulates water balance, the second simulates farmer behavior, and the third assesses farmer profits. Two scenarios are explored: Scenario I introduces penalties for groundwater overexploitation, and Scenario II implements awareness raising and training to encourage using modern irrigation systems. The results show that penalties lead to reductions in water requests exceeding limits by 8%, 45%, and 68% for fines of 1000, 5000, and 10,000 IRR·m⁻³, with corresponding net profit decreases of 1.3%, 8.0%, and 11.6%. The ranges of farmer cooperation for groundwater management vary from 20% to 50% over the 10-year simulation period. In Scenario II, increasing the radius of awareness from 0.5 to 2 km

substantially increases the adoption of modern irrigation from 1457 to 2057 farmers. These findings highlight how different policy measures impact various types of farmer based on their specific characteristics and preferences.

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1 Introduction

The integration of human and water resources systems reveals a range of complexities such as variability, unexpected feedbacks loops, abrupt variations, and nonlinearity, all due to the intricate nature of human behavior. In multi-agent decision-making, agent decisions are deeply dependent to each other, often leading to conflicting objectives^[1]. Recently, agent-based modeling has been increasingly used for simulating complex systems^[2]. Such models are well-suited for addressing social issues, as they offer valuable insights into human behavior and their interactions^[3]. They are particularly effective in modeling the decision-making processes of diverse and heterogeneous groups^[4]. Given that they allow for the representation of each agent, whether human or non-human, as an independent unit capable of interacting with other agents^[5].

The concept of agent-based modeling was developed in the late 1940s when it was first expressed in relatively simple terms. It did not undergo any further development until 1990 due to high computational costs. Significant advancements in the field began with the introduction of *StarLogo* in 1990. This was followed by the emergence of *Swarm* and *NetLogo* in the mid-1990s; *RePast* and *AnyLogic* simulation software in 2000; and *GAMA* in 2007. The concept of agent-based modeling has been applied in a variety of fields, with models evolving to simulate not only social interactions among humans^[6] but also the behavior of organizations and decision-making processes^[7]. Davidsson et al.^[8] explored agent-based modeling in eight areas of animal, psychological, social, organizational, economic, ecological, robotic, and transportation systems. Water resources systems are categorized under ecological systems, with agricultural, domestic, and industrial users represented as human agents within these models^[9].

A substantial number of studies have explored various aspects of user behavior and decision-making related to water resources usage^[10–12], including impacts of motivational strategies on water-user behavior and water consumption^[13–18], establishing networks among users and their capacity to be influenced by training and publicity^[19–21], development of a groundwater market^[22], and also coupling agent-based and

optimization models for domestic water management^[23]. Scenarios defining is an effective method for assessing water consumption and quality through various policies such as incentive plans^[13], cap and trade systems^[24], and initiatives aimed at awareness raising and training for water users^[16]. While many agricultural management models have been developed that can incorporate technical parameters and variables such as sensitivity to water stress, plant growth stage, soil type, and crop yield^[15], there has been limited simulation of how farmers accept these policies and scenarios.

Investigation of user behavior commonly involves defining the characteristics of user agents. In an agriculture context, for example, farmer characteristics as an agent might include water and land types, available capital, labor resources, cropping pattern, and risk tolerance^[10,25]. Also, a number of studies have been conducted that social and economic changes within farming communities can influence the norms governing water resource utilization. Some researchers advocate for enhancing intersector coordination within river basins and promoting the involvement of diverse social groups to enhance the river basin organization^[26]. These norms tend to be flexible, allowing users to adapt their actions based on shifting climatic and economic conditions. For example, during droughts, consumers may resort to unauthorized actions, such as illegal well extraction, if their water needs are not satisfactorily met within the existing regulations^[27].

Researchers emphasize that public opinion is crucial for determining how water resources are managed. The attitudes and beliefs of the general public toward water usage substantively impact their acceptance or rejection of management strategies proposed by authorities. Understanding the dynamic nature of public opinion and the relationships formed among farmers is key in shaping their reactions to management initiatives^[20]. While many researchers acknowledge the limitations of dominant top-down approaches that have led to ecological crises in some parts of the world^[28,29], some have attempted to train agents to change cropping patterns and optimize benefits. However, agent behavior in these studies often follows an optimization approach that may not be accepted by users in real-life conditions.

The objective of this study was to examine the water management policies proposed by authorities based on simulation of changes in farmer behavior. Specifically, this research aimed to determine how farmer decisions are influenced by alterations in water policies, as well as to analyze the impact of these water policies on the profitability of farmers and the cooperation level between farmers. For this purpose, it was essential to simulate the behavior of individual farmers or groups of farmers. This was achieved through agent-based modeling, where each farmer was represented as a separate agent with unique characteristics and decision-making abilities. Agent-based modeling allows for the aggregation of farmer decisions and their impact on the overall water resources system. This approach enabled a bottom-up analysis of the system, providing valuable insights and feedback on how farmer actions can affect water resources.

Previous studies have simulated various water management policies aimed at groundwater conservation and profitability of farmers. However, these studies predominantly used a top-bottom approach to farmer decision-making such as optimization models. Also, the characteristics of farmers in term of water-saving behavior and cooperation with other farmers to preserve groundwater have not been thoroughly investigated. This is crucial, considering that certain scenarios may benefit some agents while being detrimental to others. In addition, previous studies have not simultaneously used both top-bottom and bottom-up approaches.

The primary contribution of this paper lies in the simultaneous evaluation of the effect of farmer decisions in response to water policies on groundwater management, as well as the effect of water policies on farmer profitability. The research aims to determine the changes in farmer behavior in different scenarios and evaluate their effects on groundwater resources. Given its objective, this study integrated both top-down and bottom-up approaches, presenting a novel methodological framework. Most previous research has focused on a top-down viewpoint, using game theory methods or optimization models to simulate farmer behavior and demonstrate the results of decision-making. However, not all consumers operate under a rational or optimal framework, and they do not all act in the same way. The most important contribution of this research is the detailed modeling of agents, allowing for the examination of how different scenarios affect each individual farmer. The proposed model demonstrates the effects of water policies and scenarios on each agent, analyzing the success of each scenario in fostering cooperation among farmers. Differences in farmer behavior, whether cooperative or non-cooperative, as well as the level of cooperation among farmers, are explicitly

simulated. The results for different farmers are presented, illustrating how decisions and effects vary for each farmer.

2 Material and methods

This section provides a description of the research steps shown in Fig. 1 that were designed and performed to achieve the objectives of the study.

Step 1: The first part in this step consisted of collecting data used to develop the water resources model. The data required included amounts of water exploitation, precipitation, evaporation, inflows and outflows of both ground and surface water resources, infiltration rates for both ground and surface flows, and infiltration due to return flows from different uses. The data used had been reported by the Iranian Ministry of Energy^[30]. A system dynamics model was used to simulate groundwater inputs, outputs and feedbacks mechanisms. The system dynamic model developed can be well linked with agent-based modeling in the *AnyLogic* environment.

Step 2: The conceptual framework of agent-based behavior model was developed within the software environment. According to the information obtained previous part, behavioral rules and relations based on farmer characteristics, and capital properties including cultivated area, types of crops, available water resources were designed. Then an optimization model is also developed to minimize the differences between the values observed and those predicted by the model. For this goal the optimal parametric coefficients involved in water balance equation, including those of infiltration, water storage and return flows, were calculated and used to parametric function to apply in water resources model.

Step 3: The behavioral model was then calibrated and verified in the third step after the two behavioral and water resources models were coupled and the behavioral coefficients were determined. In this step, the two behavioral and water resources system models were integrated into one model once their shared variables are determined. This provided the basis for deriving a combined behavioral-water resources model that is then subjected to calibration and validation by varying the coefficients of the behavioral model and comparing the resulting output on aquifer water balance with that obtained from the water resources model (developed in the first step).

Step 4: The scenarios were introduced into the unified behavioral-water resources model and the results obtained were analyzed.



Fig. 1 Development stages of the behavioral and water resources model.

2.1 Structure of the proposed agent-based model and its components

The following three subsystems were developed for the purposes of this study. The first subsystem simulates the behavior of human agents while the second one simulates the water resources system. To link the two models, it was necessary to identify their shared variables. This identification allowed for both direct integration and the examination of their

interactions over a period of time. The third subsystem captured the profits made by farmers based on their activities. A brief description of the human agent behavioral simulation is presented below, and the functions and rules used are introduced.

In the system developed, agricultural farmers were designated as first-level agents, while water managers serve as second-level

agents. Farmers base their decisions on the policies established by water managers, whose primary goals are to meet farmers' needs and ensure the sustainable conservation of water resources. Conversely, the main objective for farmers is to maximize their profits. As a result, each agent behaves according to their specific goals. Interactions among agents can take various forms, including training to enhance knowledge, information exchange for decision-making, implementation of new water management policies, and monitoring to ensure compliance with legal regulations regarding water usage.

2.1.1 Equations governing agricultural farmer behavior

The primary factor influencing the behavior of farmers is the profits generated from agricultural activities, which are directly affected by water consumption. Water consumption is further influenced by regional climatic conditions and precipitation levels; decreased precipitation leads to greater reliance on groundwater resources. When surface water availability diminishes, users, who draw from both surface and groundwater resources, tend to increase their dependence on groundwater. Additionally, user behavior is influenced by the actions of their peers, meaning that farmers are likely to adapt their practices in response to behavior of their neighbors. Equations (1) and (2) represent the transition of agent attitude from a cooperative to a cooperative and non-cooperative stance, respectively. Equations (3) and (4) represent the shift in attitude from a non-cooperative to both non-cooperative and cooperative behavior, respectively.

$$BF_{S_t, T+1, t+1}(C \rightarrow C) = \mathbf{a} \left(\frac{1}{T} \sum_{i=1}^T \left(\frac{NB_{DecWatUse}}{MaxNB} \right)_i \right) + \frac{1}{p} \left(\sum_{n=1}^p \frac{y_{n, DecWatUsed, t}}{Y_{Max, n}} \right) + \mathbf{b} \left(\frac{P_{t+1}}{P_{Wet}} + \frac{SAW_{t+1}}{SAW_{wet}} \right) + \mathbf{c}' \left(\frac{1}{t} \sum_{i=1}^t NM_yCo + \frac{NCoNe_t}{TNe} \right) \quad (1)$$

$$BF_{S_t, T+1, t+1}(C \rightarrow NC) = \mathbf{a} \left(\frac{1}{T} \sum_{i=1}^T \left(\frac{NB_{WatUse}}{MaxNB} \right)_i \right) + \frac{1}{p} \left(\sum_{n=1}^p \frac{y_{n, WatUsed, t}}{Y_{Max, n}} \right) + \mathbf{b} \left(\left(1 - \frac{P_{t+1}}{P_{Wet}} \right) + \left(1 - \frac{SAW_{t+1}}{SAW_{wet}} \right) \right) + \mathbf{c} \left(\frac{1}{t} \sum_{i=1}^t NM_yNC_o + \frac{NCoNe_t}{TNe} \right) \quad (2)$$

$$BF_{S_t, T+1, t+1}(NC \rightarrow NC) = \mathbf{a} \left(\frac{1}{T} \sum_{i=1}^T \left(\frac{NB_{WatUse}}{MaxNB} \right)_i \right) + \frac{1}{p} \left(\sum_{n=1}^p \frac{y_{n, WatUsed, t}}{Y_{Max, n}} \right) + \mathbf{b} \left(\left(1 - \frac{P_{t+1}}{P_{Wet}} \right) + \left(1 - \frac{SAW_{t+1}}{SAW_{wet}} \right) \right) + \mathbf{c}' \left(\frac{1}{t} \sum_{i=1}^t NM_yNC_o + \frac{NCoNe_t}{TNe} \right) \quad (3)$$

$$BF_{S_t, T+1, t+1}(NC \rightarrow C) = \mathbf{a} \left(\frac{1}{T} \sum_{i=1}^T \left(\frac{NB_{DecWatUse}}{MaxNB} \right)_i \right) + \frac{1}{p} \left(\sum_{n=1}^p \frac{y_{n, DecWatUsed, t}}{Y_{Max, n}} \right) + \mathbf{b} \left(\frac{P_{t+1}}{P_{Wet}} + \frac{SAW_{t+1}}{SAW_{wet}} \right) + \mathbf{c} \left(\frac{1}{t} \sum_{i=1}^t NM_yCo + \frac{NCoNe_t}{TNe} \right) \quad (4)$$

where, T is year in the simulation period, t is month in the simulation period, $\frac{1}{T} \sum_{i=1}^T \left(\frac{NB_{WatUse}}{MaxNB} \right)_i$ is average ratio of profit to maximum profit in previous years, if water exploitation from the well is equal to water demand, $\frac{1}{p} \left(\sum_{n=1}^p \frac{y_{n, WatUsed, t}}{Y_{Max, n}} \right)$ is ratio of average to maximum yield of each crop in previous months, if water exploitation from the well is equal to the water demand, $\frac{P_{t+1}}{P_{Wet}}$ is ratio of precipitation in the time point $t + 1$ to that in a wet month during the statistical period available, $\frac{SAW_{t+1}}{SAW_{wet}}$ is ratio of surface water available in the region during the time point $t + 1$ to that in a wet month throughout the statistical period, $\frac{NCoNe_t}{TNe}$ is ratio of non-cooperative neighbors in the previous month to the total number of neighbors, $\frac{1}{T} \sum_{i=1}^T \left(\frac{NB_{DecWatUse}}{MaxNB} \right)_i$ is average ratio of profit to total profit in previous years when water exploitation from the well is accomplished according to the policies dictated by the managers, $\frac{1}{p} \left(\sum_{n=1}^p \frac{y_{n, DecWatUsed, t}}{Y_{Max, n}} \right)$ is average ratio of the yields of different crops to the maximum yield of each crop in previous months when water exploitation from the well is accomplished according to the policies dictated by the managers, $\frac{1}{t} \sum_{j=1}^t NM_yCo$ is ratio of the cooperative attitude of each user to his/her total attitudinal states, and $\frac{NCoNe_t}{TNe}$ is ratio of cooperative neighbors in the previous month to the total number of neighbors. Also, a , b , c , and c' represent effectiveness coefficients whose ranges are determined based on previous study results, expert views, and the results obtained from the optimization model.

2.1.2 Equations governing water manager behavior

Water managers (second-level agent) design water resources management scenarios in accordance with the policies and procedures defined by water laws and regulations. In this study, two scenarios are developed, the first focusing on imposing penalties on users who overexploit water during the simulation period (the threshold is set by water managers). This scenario is implemented by introducing penalties and changing part of Eqs. (2) and (3), $\left(\frac{1}{T} \sum_{i=1}^T \left(\frac{NB_{WatUsed_CFine}}{MaxNB}\right)_i\right)$, to investigate user behavior. The amount of the penalty is obtained from the following equation:

$$CFine = \sum_{i=1}^t VolW_i \times Pr_{illExpo} \quad (5)$$

where, $CFine$ is the penalty for overexploitation of each agent during their consumption period, $VolW_i$ is the volume of water exploitation by each user agent, $Pr_{illExpo}$ is the penalty for 1 m³ of overexploited water.

The second scenario focuses on promoting awareness and education regarding modern irrigation technologies. In this approach, selected users undergo specialized training that equips them with the knowledge and skills necessary to implement these advanced irrigation methods. Subsequently, these trained users serve as facilitators, educating and mentoring their peers in the effective use of modern irrigation technologies.

2.2 Profit estimation subsystem

The main interaction between water managers and users through the policies implemented by water authorities affects user profits. In the agriculture sector, the profit function reflects the difference between revenues and costs of agricultural production as shown in Eq. (6).

$$Netbenefit = Benefit - Cost \quad (6)$$

where, $Netbenefit$ is the net profit due to agricultural activity (IRR), $Benefit$ is the revenues accrued from agricultural activity (IRR), $Cost$ is the costs associated with agricultural activity (IRR). This leads to the following equation:

$$Benefit = \sum_{p=1}^n (p_p \times y_p \times A_p) \quad (7)$$

where, p_p is crop price (IRR·kg⁻¹), y_p is actual yield of crop p (kg·ha⁻¹), and A_p is area under crop p (ha).

The actual yield of crop is calculated as follows:

$$y = Y_{max} \prod_{t=1}^m \left(1 - ky_t \times \left(1 - \frac{Alloc_t}{Dem_t}\right)\right) \quad (8)$$

where, Y_{max} is maximum crop yield (kg·ha⁻¹), ky_t is crop sensitivity to water stress, $Alloc_t$ is volume of allocated water from the sum of ground and water resources (m³ per month), and Dem_t is water demand (m³ per month). It is important to notice that the amount of $Alloc_t$ in Eq. (8) varies based on the cooperative or non-cooperative behavior of farmers. When farmers exhibit non-cooperative behavior, the volume of allocated water ($Alloc_t$) in that time point will meet the amount of water demand (Dem_t). However, if farmers behave cooperatively, the volume of allocated water ($Alloc_t$) will meet a portion of the water demand as determined by the scenarios.

The total agricultural production costs, $Cost$ (IRR) is obtained as follows:

$$Cost = \sum_{p=1}^n (Sw_pri \times alloc_surf_p + Co_{t,p} \times A_p) + \frac{9.81}{1000\eta} \sum_{t=1}^m (Q \times T_t \times h_t \times Ele_pri) \quad (9)$$

where, $SW-Pri$ is surface water price (IRR·m⁻³), $alloc_surf_p$ is volume of allocated water (m³), $Cost_p$ is crop production costs (IRR·ha⁻¹), η is pump efficiency (%), Q is well discharge rate (L·s⁻¹), T_t is duration of water exploitation from the well (h per month), h_t is water level (m), and Ele_pri is power price (IRR·kWh⁻¹).

2.3 Water resources simulation subsystem

The water balance equation is a critical tool for assessing variations in aquifer water levels, particularly the factors and parameters influencing groundwater recharge. Equation (10) is the general form of water table fluctuation for groundwater resources used to determine variations in aquifer water level at each time point:

$$\Delta H_t = \frac{\Delta V_t}{A_e \times S} \quad (10)$$

where, ΔH_t is water table fluctuation (m), ΔV_t is variations in water volume (m³), A_e represents the area of aquifer (m²), and S is a groundwater storage coefficient. Equation (11) is used to calculate variation in water volume in an aquifer at time point t as follows:

$$\begin{aligned} \Delta V_t &= Inflow_t - Outflow_t \\ &= F(P_t, a_1, a_2, c_1, c_2, b, Cons, d, e, f, Evap, OutGW, B.f, C, L, D) \end{aligned} \quad (11)$$

where, $Inflow_t$ is the flows that recharge the groundwater resource, and $Outflow_t$ is flows discharged from the groundwater resource. The components of $Inflow$ consist of P_t (m per month), that is amount of precipitation in plain or area of heights in time point t , a_1 , and a_2 are conversion factors of

precipitation in heights and in plains to groundwater inflows, respectively. Also, c_1 and c_2 are the conversion factor of the surface runoff formed in the plain and in the height (emerging from an aquifer) to infiltration of the aquifer, respectively. The variable b represents the conversion factor of precipitation over the aquifer area to percolating of the aquifer. One of the other components that have effect on the recharge of the groundwater resource, are return flows from different uses; where d , e , and f are rates of return flow into the aquifer from agricultural, industrial and domestic water consumption, respectively.

The components of *Outflow* include, *Cons* (m^3 per month) that is water consumption by different sectors, *Evap* (m^3 per month), is evaporation from the aquifer and *OutGW* (m^3 per month), is outflows from the aquifer. In the area of this research, the river might serve as either a recharge or a draining depending on aquifer and the river flow conditions and in Eq. (11), C (m^3 per month) is rates of water transfer from/into the river, L (m) is the recharging or draining stretch of the river, D (m) is width of the wetted part of the river, $B.f$ is boundary flow is the amount of flow that if the river flow be larger than it the river acts as a recharge resource and if the river flow be less than it, the river acts as a draining.

Then an optimization model is developed for determining optimal values for a_1 , a_2 , c_1 , c_2 , b , d , e , f , C , S , and $B.f$. Equation (12) is used to calculate the value for the objective function that consists of the sum of differences between observed and predicted values for groundwater level over the simulation period (Z).

$$\text{Min}Z = \sum_{t=1}^n (\text{abs}(H_{\text{obs}}(t) - H_{\text{sim}}(t))) \quad (12)$$

where, $H_{\text{obs}}(t)$ is observed groundwater level in month t , and $H_{\text{sim}}(t)$ is simulated groundwater level in month t . The objective function is minimized using the Particle Swarm Optimization (PSO) algorithm that uses a randomly generated initial population.

2.4 Coupling the behavioral and water resources subsystems

The main objective behind behavioral modeling is to assess how changes in farmer behavior affect variations in water exploitation and aquifer water level. Therefore, it is essential to link the behavioral and water resources subsystems, particularly when management scenarios are implemented. To facilitate this integration, a variable has been assigned to each well that is common to both subsystems, allowing it to be

accessed both of behavioral and water resources subsystems. When a scenario is active, the cooperative or non-cooperative behavior of each farmer is simulated using Eqs. (1)–(4) and the value of BF is calculated within behavioral subsystem. If farmers behave cooperatively, they will adhere to the scenario, leading to a reduction in water exploitation and ensuring that the allocated water meets part of the demand. Conversely, if they behave non-cooperatively, they will prioritize meeting their demand regardless of the scenario.

The simulation of both farmer behavior and the water resources system, along with their interactions, is conducted using *AnyLogic* software, which is capable of performing simulations in both agent-based models and system dynamics. This platform supports both agent-based models and system dynamics, providing a robust graphical environment and benefiting from significant advancements due to its extensive applications.

2.5 Study area

The study area of Lenjanat is a sub-basin of Gavkhooni basin, located between $50^\circ 30'$ to $53^\circ 23'$ E and $32^\circ 10'$ to $30^\circ 40'$ N. It encompasses a total area of 3365 km^2 with plains covering 1619 km^2 . In this area, water demands are met through both surface and groundwater resources. The only source of surface water inflow to the region is the Ben-Saman station, which has an outflow of 1359.2 million cubic meters (MCM). A portion of the water flow is used to supply for the agricultural and industrial demands in the region. The total outflow from this region is about 535.5 MCM, that flows into downstream regions^[30]. Table 1 reports the details of water consumption in the region and the sources of supply.

Both orchard and farm cultivated areas as well as the total irrigated area are given in Table 2 for 6 periods over 10 years. Notably, the area for orchards increased from 14% in 2004 to 25% in 2014, while the area for cultivation decreased from 86% in 2004 to 75% in 2014. During the same 10-year period, the total irrigated area decreased by 35%. The crops grown in the region typically include wheat, barely, rice, lucerne, maize, potatoes and onions while the orchard products consist of grapes, almonds, walnuts, apples, apricots, pomegranates, and peaches. Figure 2 show the revenues, costs, and net profits for crops cultivated in Lenjanat region during the fiscal year 2010–2011. Notably, rice production recorded the highest cost and generated the highest revenues, while apples yielded the highest net profit. Potatoes recorded the lowest revenues and costs, while maize had the lowest net profit.

Table 1 Water consumption volumes (MCM) in the Lenjanat study area

Water resources	Plain			Total		
	Urban	Agriculture	Industrial	Urban	Agriculture	Industrial
Groundwater	3.4	175	0.5	5.4	197	0.7
Surface water	23.8	187	84.9	23.8	190	84.9
Total	27.2	362	85.4	29.2	387	85.6

Table 2 Irrigated areas in different years in the study area

Year	Cereal cultivated area (ha)	Garden cultivated area (ha)	Total (ha)
2004–2005	25,150	3897	29,047
2006–2007	25,245	4521	29,766
2008–2009	16,894	4645	21,539
2010–2011	15,652	5010	20,662
2012–2013	15,031	4576	19,607
2014–2015	13,948	4587	18,535

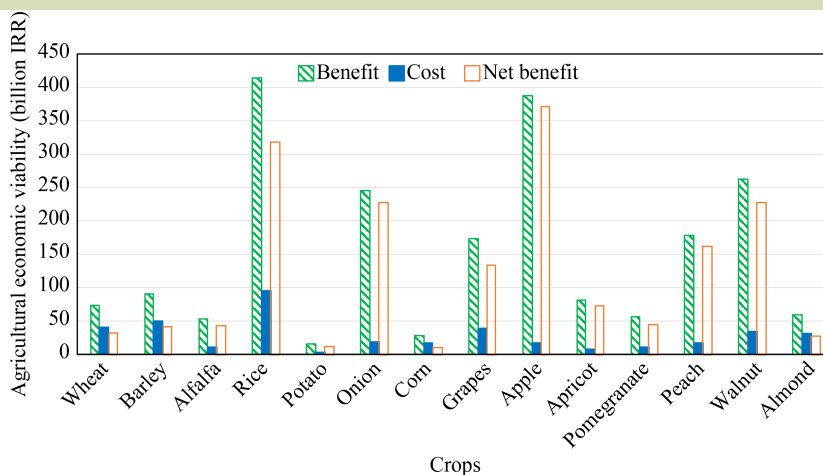


Fig. 2 Agricultural benefits, costs, and net benefits in Lenjanat region.

Due to the reduction of surface water resources and high growth of water demand in industrial and urban in the area of the study in recent years, there has been a rise in well usage, resulting in a decline in groundwater levels. Currently, farmers are inclined to fully satisfy their water needs, and many exhibit non-cooperative behavior. As long as the farmers follow non-cooperative behavior, the more overexploitation occurs. In this study, the interconnected decision of policymakers and farmers is simulated. The Lenjanat area is selected as the case study due to of the availability of detailed agricultural data and the water scarcity challenges it faces, which are common in many arid regions in Iran.

3 Results

This section starts with a description of the methodology used to calibrate both the water resources system and behavioral models. Following calibration, these models are applied to implement scenarios developed by water managers within the integrated behavioral and water resources system model.

To employ the water resources model under different scenarios and hydrological conditions, it was first essential to determine the values for the coefficients (e.g., infiltration rates and rates of return flows from different uses) that affect the water balance

in the aquifer. For this purpose, at first, the optimization model was used for a 96-month period with the objective of minimizing the sum of differences between observed and predicted values of groundwater levels. The results from the optimization model are presented in Table 3. Figure 3 presents the historical and simulated values of groundwater levels of the calibration over 96 months and validation over 24 months.

As mentioned in Section 2.5, due to their inherent complexities, calibration and validation were done for both groundwater and behavioral models. The behavioral model was calibrated after it have been linked with the water resources model. The optimal values of the coefficients a , b , c , and c' were obtained based on most agreement between coupled model results and historical values of groundwater fluctuations. The based values of a , b , c , and c' are 10, 5, 0.3, and 0.7.

4 Discussion

This section explores the outcomes of two different scenarios.

In the first scenario, penalties are imposed for excessive water use beyond legally allowed limits. Certain research indicates a low perceived value of water^[31], with a significant gap between its true value and its price, particularly in this region^[32]. In the absence of penalties, farmers frequently tend to overexploit water from wells, exceeding the permitted limits. To address this issue, the first scenario focuses on regulating water use by imposing penalties for violations. Acknowledging that farmers may lack inclination toward adopting water-saving technologies^[31], the second scenario was designed to assess the impact of awareness campaigns on encouraging the adoption of modern irrigation systems. Experts suggest that if leading farmers adopt modern irrigation methods, others are likely to emulate them.

4.1 Scenario I: Imposing penalties for excessive water use beyond legal limits

In this scenario, the primary assumption is to offer farmers the

Table 3 Calibration (96 months) and validation (24 months) results of the water resources model

Parameter	Description	Initial value	Best value
a_1	Conversion factor of precipitation in heights	[0.02, 1]	0.025
a_2	Conversion factor of precipitation in plains	[0.1, 0.25]	0.21
b	Conversion factor of precipitation over the aquifer area to percolating of the aquifer	[0.1, 0.25]	0.24
c_1	Conversion factor of the surface runoff formed in heights	[0.001, 0.01]	0.0078
c_2	Conversion factor of the surface runoff formed in plain	[0.01, 0.05]	0.0356
d	Return flow into the aquifer from agricultural water consumption	[0.2, 0.35]	0.222
e	Rate of return flow into the aquifer from industrial water consumption	[0.08, 0.12]	0.0945
f	Rate of return flow into the aquifer from domestic water consumption	[0.5, 0.75]	0.565
S	Groundwater storage coefficient	[0.025, 0.06]	0.0385
C	Rates of water transfer from/into the river	[0.01, 0.08]	0.01
B,f	Boundary flow	$[10^7, 2.7 \times 10^8]$	1.58×10^7

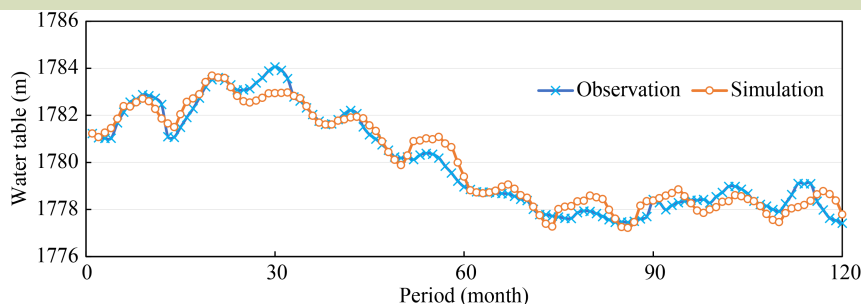


Fig. 3 The historical and simulated values of groundwater levels of the calibration (96 months) and validation (24 months).

choice between reducing their water consumption within specified limits or facing a penalty for exceeding those limits. Additional assumptions for this scenario included:

(1) All wells are equipped with active water meters throughout the entire simulation period. If overexploitation is detected, farmer connection is suspended, and the violator must report to the water manager.

(2) The simulation spans a 10-year time frame, with a penalty exemption during the first year where farmers who report violations are only informed. Penalties for overexploitation come into effect from the second year onwards.

(3) To analyze the impact of penalties on farmer behavior and aquifer water table fluctuations, fines are set at five levels: 100, 1000, 2000, 5000, and 10,000 IRR-m⁻³ for overexploitation.

(4) While the government has set a fine of 100 IRR-m⁻³ for overexploitation, experts consider this amount insufficient. The fine of 10,000 IRR-m⁻³ is equivalent to the water price paid by industries in the area. The study includes these five penalty levels to demonstrate how water demand changes with varying fines.

(5) The Iranian Ministry of Energy reports that overexploitation accounts for 20% of current groundwater usage^[30]. It is imperative to curb this overexploitation within a specific time frame. Water managers have adopted policies aiming for a 20% reduction in water consumption over the entire simulation period, translating to an annual reduction rate of 2%.

Figure 4 shows water table fluctuations in the aquifer under different penalty values. The model was run for penalties ranging from 100 to 10,000 IRR-m⁻³. The figure also compares the target conditions (20% reduction in water consumption by the end of the simulation) with the current conditions (without any penalty policy in place). Figure 4 shows that imposing a penalty of 100 IRR-m⁻³ for exceeding the water exploitation limit did not lead to a significant change in farmer behavior, with results similar to the present conditions. However, a sharp increase in the penalty to 1000 IRR resulted in a noticeable impact, leading to a 0.3-m rise in the aquifer water level by the end of the simulation period. This effect was even more pronounced when the penalty was further increased to 10,000 IRR, causing a 2.2-m increase in the water level. Despite these changes, the water level remained 1 m below the target level. In conclusion, farmers showed little response to low penalty levels, while achieving the target water level required substantially higher penalties.

Several studies employing various methodologies have been conducted to assess the current state of the Zayandehroud River basin, with a particular focus on Lenjanat as a critical region. One study, which applied optimization techniques to determine an optimal cropping pattern, found that the ideal cultivation strategy led to a 40% increase in income and a 3-m rise in groundwater levels over a 10-year period^[32]. Despite these promising results, the practical scenario often reveals that farmers tended to stick to their current cultivation practices rather than adopting the recommended optimal pattern. It should be noted that farmers might not possess comprehensive environmental awareness or the capacity to tackle intricate optimization challenges^[33]. The findings indicating a 2.2-m

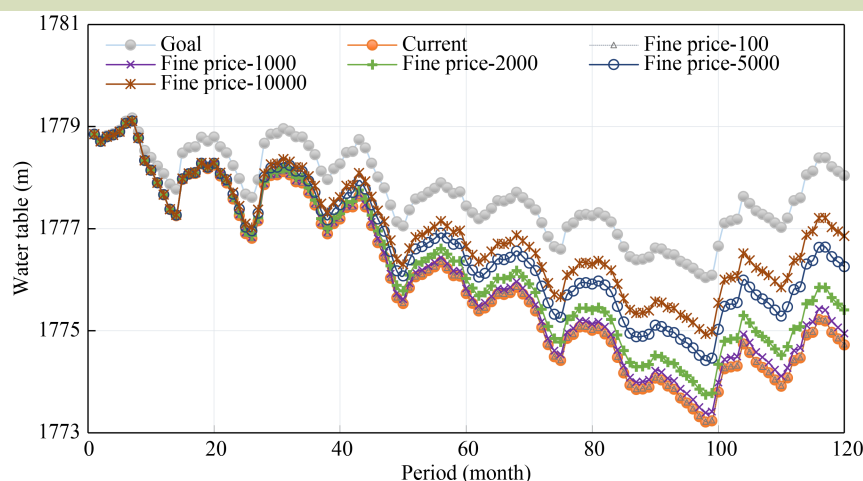


Fig. 4 Variations in water level in the aquifer for different penalties.

increase in groundwater levels across 10 years, coupled with a penalty of 10,000 IRR·m⁻³, suggest that this model provides a more realistic projection compared to the 3-m rise observed in the earlier study.

The level of non-cooperation exhibited by farmers in response to varying water penalties was analyzed throughout the entire simulation period. According to the findings presented in Fig. 5, when a water penalty of 100 IRR·m⁻³ was imposed, 76% of farmers consistently exceeded the allowed water limit and exhibited no cooperation throughout 100% of the time points. It is evident that all farmers display a non-cooperative stance for at least 75% of the simulation period. As penalties increased, farmer cooperation improved, but even at higher penalty levels, all farmers maintained a non-cooperative stance for at least 25% of the simulation period.

various water penalties. In the first year, the absence of penalties results in an excess water demand of 29.6 MCM. However, as penalties were introduced, this demand substantively decreases in subsequent years. For instance, in the second year, excess water demand dropped to 16.6 MCM and further declined to 5.2 MCM as penalties increased from zero to 10,000 IRR·m⁻³, representing a reduction to nearly one-third. This trend continued over the following years. Notably, fluctuations in excess water demand across the years were influenced by changes in water needs of farmers. In the fourth year, excess water demand exceeded that of other simulated years, likely due to climatic conditions that increased the need for irrigation.

This study offers valuable insights into cooperative behavior of farmers in response to varying penalty amounts for water usage. The extent of non-cooperative behavior and the amount of water consumption was quantified using simulation results

Figure 6 shows the differences in excessive water demands for

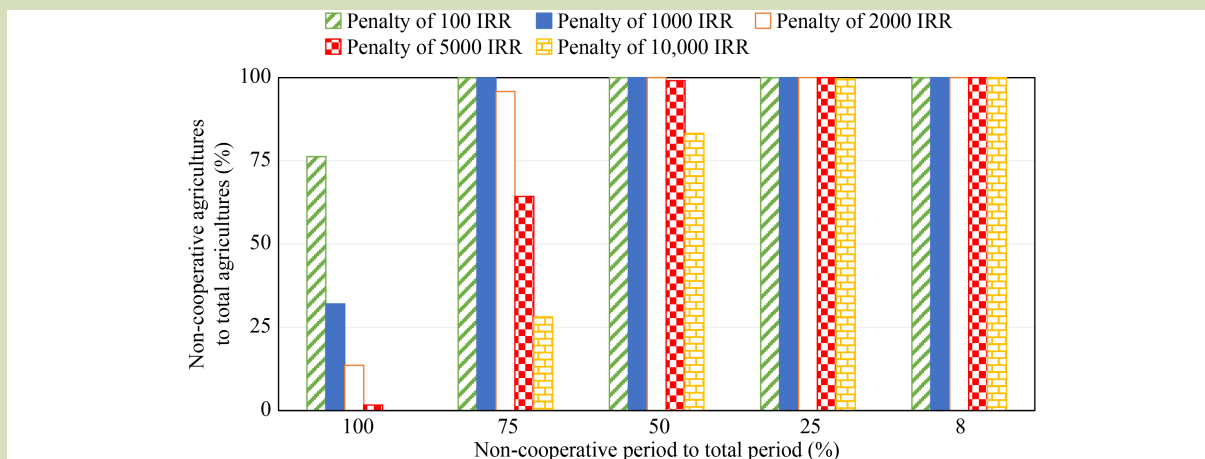


Fig. 5 Farmer non-cooperation throughout the simulation period.

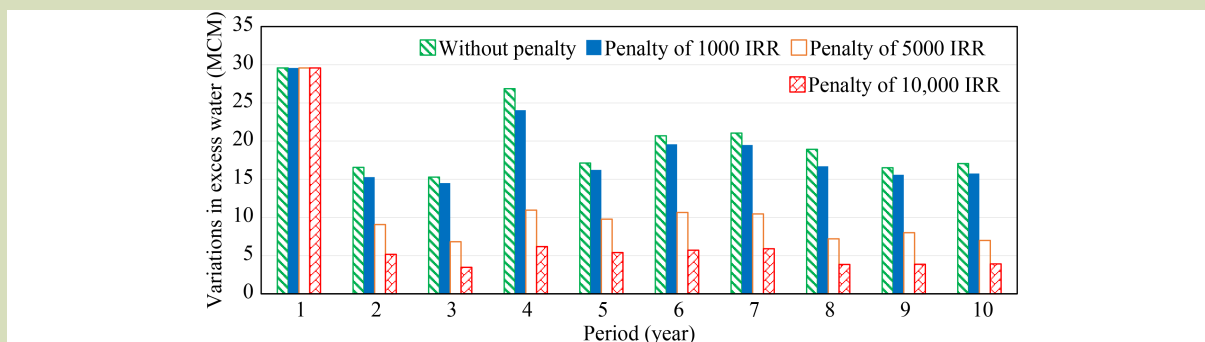


Fig. 6 Excess water demand changes in response to water penalties during the simulation period.

with different penalty levels. This is a significant contribution of this study, as previous studies on water management policies often neglected the behavioral patterns of the beneficiaries. The impact of different penalty levels on farmer profits is shown in Fig. 7. A penalty of 100 IRR·m⁻³ resulted in less than a 0.5% decrease in profits across the years. The most significant reduction of 20.5% in net profits occurred in the fourth year under an excess water penalty of 10,000 IRR·m⁻³, dropping profits from 1603 to 1274 billion IRR.

4.2 Scenario II: Knowledge dissemination and advocacy for modern irrigation systems

This scenario explores the impact of knowledge dissemination and advocacy on the adoption of modern irrigation systems within a simulated agricultural community. This scenario was based on the following assumptions:

- (1) Initial training: 10% of the pioneer agricultural farmers receive training on modern irrigation systems in the first year of a 10-year simulation period, these trainees become advocates for the technology from the second year.
- (2) Neighborhood radius: the trainees disseminate their knowledge through messages or publicity within a radius (r) among their fellow users up from their water supply; allowing for the analysis of neighborhood radius influence on knowledge diffusion.
- (3) Radius variation: to determine the effect of neighborhood radius on knowledge dissemination among users, the model is

run for neighborhood radii of 0.5, 1, 2, and 5 km.

- (4) Continuous advocacy: from the second year onward, trained users provide every fortnight training and publicity on modern irrigation systems to their peers.
- (5) Phased installation: due to limited public funding, users are required to install modern irrigation systems on 10% of their cultivated land area annually.
- (6) Phased installation: due to limited public funding, users are required to install modern irrigation systems on 10% of their cultivated land area annually.
- (7) Adoption trigger: users who receive two instances of the messages and/or publicity regarding modern irrigation systems throughout the simulation period are required to adopt the technology.
- (8) Continuing advocacy: users who have already installed modern irrigation equipment are required to participate in furthering the advocating program.
- (9) Agent representation: each well in the study (totaling 2096) represents a user and serves as an agent in the dissemination process.

Figure 8 shows the percentages of users adopting modern irrigation systems over the simulation period. The results indicate that, for a neighborhood distance of 0.5 km, 1457 (69%) users received the publicity messages or training and

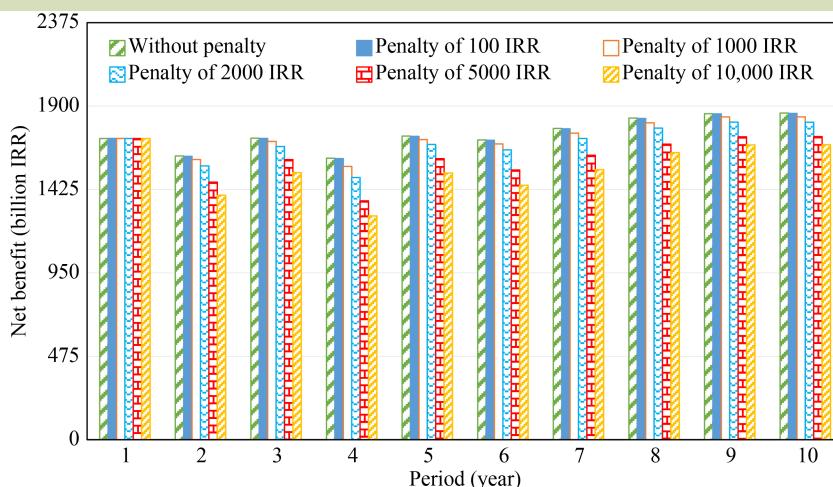


Fig. 7 Variations in net crop profits throughout the simulation period.

show their interest in modern irrigation systems during the simulation period. Increasing the radius led to a significant rise in adoption, with all 2096 users within a 5-km radius becoming convinced of the need for modern irrigation systems. Also, it can be seen from this figure that a concentrated period of knowledge dissemination and adoption within the first 3 years of the simulation period. While there was a slight increase in new adopters after the third year, this suggests a possible limitation in reaching remote users. Expanding the neighborhood radius effectively mitigated this challenge, ensuring that all users within a 5-km reach received the message. The maximum number of users convinced to install modern irrigation systems was achieved at different points in the simulation period, depending on the radius:

- 0.5 km: 1457 users convinced in month 37.
- 1 km: 1859 users convinced in month 34.
- 2 km: 2057 users convinced in month 45.
- 5 km: 2096 users convinced in month 53.

This pattern highlights the importance of strategically adjusting the reach of knowledge dissemination to maximize adoption rates.

Figure 9 shows the impact of knowledge dissemination on aquifer water levels over the simulation period, examining different neighborhood radii (0.5, 1, 2, and 5 km). The results demonstrate a clear improvement in water level attributed to the adoption of modern irrigation systems, which substantively enhances irrigation efficiency and reduces water consumption.

They also reduce irrigation return flows, which can negatively impact the aquifer water balance. This complex interplay between reduced water use and reduced return flow has been carefully considered in this study.

Expanding the radius from 0.5 to 1 km and then to 2 km resulted in substantial water level improvements. However, further increasing the radius to 5 km yielded only marginal benefits. This aligns with the adoption patterns observed in Fig. 8, where the number of users convinced to adopt modern irrigation systems showed a diminishing increase beyond a radius of 2 km. This suggests that a radius of 2 km represents an optimal balance between the benefits of wider dissemination and the diminishing returns of reaching increasingly distant users. While larger radii might have a greater reach, the effectiveness in influencing adoption and ultimately impacting water levels plateaus.

Figure 10 highlights the gradual increase in the adoption of modern irrigation systems over the simulation period, as measured by the ratio of equipped cultivated area to the total cultivated area. A neighborhood radius of 0.5 km resulted in 41% of the cultivated area being irrigated with modern equipment at the end of the simulation period. This adoption rate rises to 79% for a radius of 1 km, representing a 1.9 times increase.

However, further expanding the radius beyond 1 km reveals a diminishing trend in land area equipped with modern systems. Increasing the radius to 2 km led to a 17% increase in the equipped area, but further increasing it to 5 km resulted in a marginal increase of only 4%. This indicates that while greater extension activities across a wider area does promote adoption,

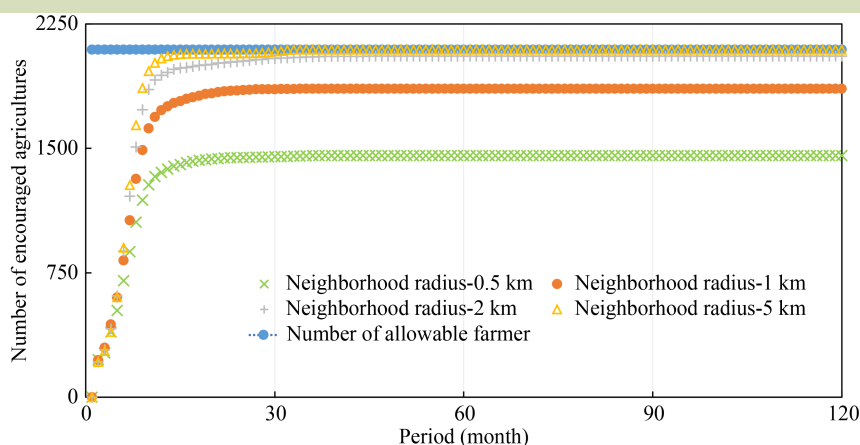


Fig. 8 Changes in the number of users encouraged to install modern irrigation system.

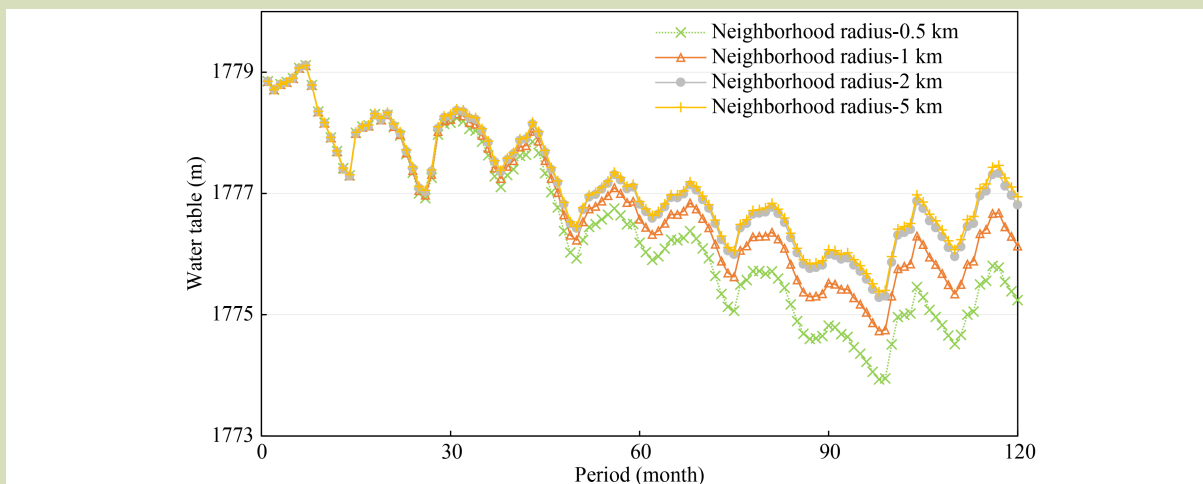


Fig. 9 Changes in the water level of the aquifer with users exposed to training or publicity for different neighborhood radii.

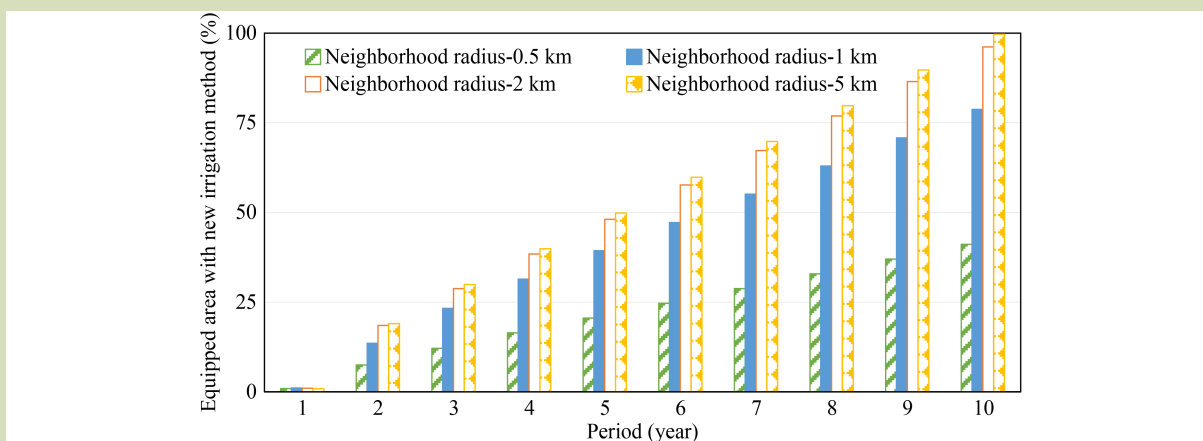


Fig. 10 Changes in cultivated area irrigated with modern systems during the simulation period.

investment in substantially increasing the equipped land area experiences diminishing returns.

Figure 11 shows the financial investment in modern irrigation system installation over the simulation period. Training and publicity peaked during the first 2 years, leading to substantial investment in installation during the second year. This spike in expenditures during the second year reflects the concentrated effort to adopt modern systems following the initial awareness campaigns. This indicates that training and publicity among users peaked in the second year. The cumulative expenditures on installing modern irrigation systems over the whole period was estimated at 212, 406, 496, and 549 billion IRR for radii of 0.5, 1, 2, and 5 km, respectively.

A detailed analysis of selected individual agent results from this scenario is presented in the supplementary materials.

5 Conclusions

This study explored the impact of farmer behavior, water management agents and their decision-making on water table fluctuations in aquifers. Using an agent-based model for farmer behavior and a system dynamics approach for water resources, the study explored how different water policies and scenarios influence decision-making among farmers and water management agents.

The paper presented two contrasting scenarios for managing

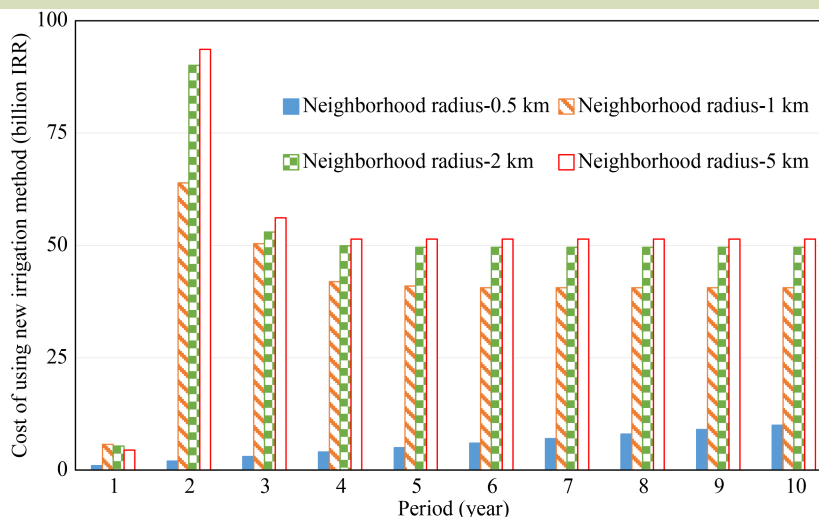


Fig. 11 Expenditures on installing modern irrigation systems.

groundwater resources. Scenario I focuses on regulating water consumption through penalties for excessive usage, while Scenario II promotes the adoption of modern irrigation systems. Both scenarios aim to reduce groundwater exploitation but employ different strategies and incur distinct costs. Under Scenario I, farmers have the option to either pay penalties or regulate their water consumption. However, the possibility of unauthorized water well drilling remains a concern. While detection of illegal wells is challenging, adhering to this scenario necessitates either reducing irrigation or adopting more efficient irrigation practices. Scenario II, in contrast, encourages the adoption of modern irrigation systems, which offer long-term benefits in reducing groundwater exploitation and eliminating the need for penalties.

Both scenarios have costs for farmers. Scenario I incurs a total penalty of 200 billion IRR over 10 years, while Scenario II requires a maximum expenditure of 514 billion IRR for implementing new irrigation methods over the same period. While Scenario I effectively curtails water consumption, it might not incentivize the adoption of modern irrigation systems. In contrast, Scenario II encourages both technological adoption and overall water efficiency. Nevertheless, the

improved water efficiency under Scenario II might inadvertently lead to expanded cultivation areas, potentially counteracting the intended reduction in groundwater exploitation. Experts opine that the second scenario stands a better chance of success due to its inclusion of educational and promotional initiatives, coupled with advancements in the irrigation infrastructure.

The research emphasizes the need for carefully planned and implemented water policies that minimize the negative impact on farmer income and ensure equitable distribution of the burden among different farmer groups. While training farmers can effectively promote the adoption of new irrigation systems, achieving successful water consumption management requires a certain level of knowledge acquisition. The study acknowledges that behavioral changes are driven by dynamic conditions, with shifts in consumer attitudes being a crucial contributing factor. Future research directions could include integrating hydrological distribution models for groundwater simulation into the existing model, expanding the study to include industrial and domestic users, and exploring the effectiveness of different information dissemination methods on farmer acceptance and adoption of water-efficient practices.

Supplementary materials

The online version of this article at <https://doi.org/10.15302/J-FASE-2024582> contains supplementary materials.

Compliance with ethics guidelines

Sayed-Ali Ohab-Yazdi and Azadeh Ahmadi declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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