Iranian Journal of Economic Studies, 11(2) 2022, 539-567

Shiraz University

Iranian Journal of Economic Studies

Journal homepage: ijes.shirazu.ac.ir

Agent-Based Simulation of Participatory Management of Groundwater Resources: A Case Study of Villagers in Isfahan Province, Iran

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Article History

Received date: 28 July 2022
Revised date: 19 November 2023
Accepted date: 13 March 2024
Available online: 06 September 2024

JEL Classification

G38
P28
Q15
Q25
R15

Keyword

Agent-based models
Large-scale irrigation systems
Participatory conservative projects
Participatory management
Tragedy of commons

Abstract

Groundwater scarcity in arid regions has become a critical issue, particularly in areas like Isfahan province, Iran, where over-extraction by farmers has led to a classic case of the tragedy of the commons. This problem is compounded by erratic rainfall and the drying of key water sources like the Zayandehroud River. In response, participatory conservation projects have been proposed, recommending the adoption of large-scale irrigation systems (LIS) to manage water resources more sustainably. However, implementing these LIS projects is complex, requiring significant financial investments and cooperation between the government and farmers, which is often difficult to secure.

To explore these dynamics, this study employs an agent-based model (ABM) to simulate farmer behavior and the adoption of LIS under different policy scenarios. The model takes into account both the limited financial resources available to the government and the intricate social structures of the villages involved. Results indicate that government financial support is crucial for fostering farmer participation, with simulations showing that when the government covers 85% of the costs, participation rates can exceed two-thirds of the community. Additionally, the study highlights an inverse relationship between village size and participation rates, suggesting that smaller villages are more likely to adopt LIS. As a result, this study recommends that financial assistance be strategically targeted, starting with smaller villages, particularly those close to water resources, while leveraging scale-free social networks to maximize adoption rates.

Highlights

- To encourage local participation in LIS construction, the government should consider the group size and social network structure.
- Simulations show that villages with lower population density have a higher likelihood of collective action in establishing LIS.
- Government financial support is crucial for encouraging villagers' participation.

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DOI: 10.22099/ijes.2024.44442.1858

1. Introduction

Agriculture plays a vital role in the livelihoods of villagers in Isfahan, with many depending on it as their primary occupation. However, the drying out of the Zayanderud River in recent years has compelled farmers to increasingly use groundwater for irrigation. This has led to a notable rise in the number of unregistered wells, with 10,000 such wells discovered out of the 50,000 wells in the region in 2018. The overexploitation of groundwater through flood irrigation has led to various problems, including land subsidence and the tragedy of the commons (Ohab-Yazdi & Ahmadi, 2018). To address these challenges and efficiently manage groundwater resources, one potential solution is the implementation of LISs, such as pressurized irrigation, instead of traditional flood irrigation methods (Cai & Xiong, 2017; Tamburino et al., 2020). These systems offer several advantages, including economies of scale. They not only support farmers who dependent on water for their crop cultivation but also enable policymakers to strategize for specific crop varieties within a single province (Small & Svendsen, 1990).

However, constructing of LISs requires significant financial investment, making the government's financial support and farmers' active participation crucial for funding these projects. Despite substantial investments in irrigation systems, they often fail to meet expectations and perform satisfactorily. Many previous systems have been unable to generate returns that at least match the opportunity cost of the investment, rendering them economically unsustainable (CERNEA & Michael, 1987; Elinor Ostrom & Gardner, 1993). Furthermore, a critical issue that is frequently overlooked is the poor performance and inadequate maintenance of these systems (Easter et al., 1987; E. Ostrom, 1992).

Since 1950, Isfahan has seen continuous development in agriculture and industrial projects. However, the region has relied on short-term solutions, like unauthorized well digging, tunnel construction, and inter-basin water transfers, to address the problems faced by beneficiaries. The growing number of beneficiaries along with recent droughts has disrupted the balance between water supply and demand. It is important to note that some short-term solutions used to combat aridity, such as dug wells, can have adverse long-term effects (El-Naqa et al., 2007; Kahneman, 2013; Scanlon et al., 2012; Schill et al., 2019; Wada et al., 2012). However, four decades of research have shown that although the tragedy of the commons (Hardin, 1968) is a persistent problem in open-access resources, it can be mitigated through the development of self-organized systems with well-designed structures (Heikkila et al., 2011; Janssen et al., 2015). Nevertheless, various factors contribute to users' willingness to accept an approach such as participatory management of common-pool resources (CPRs). Evaluating these factors in field studies can be challenging due to the complexity involved, and the scope of social science research often fails to capture all relevant events (Ghorbani, 2016).

Laboratory experiments offer potential solutions to address the problem at hand and can significantly contribute to our understanding of user behavior dynamics (Elinor Ostrom & Gardner, 1993). However, there are limitations to the number and factors that can be experimentally tested in a controlled laboratory environment. For instance, it becomes challenging to design experiments that capture the long-term interactions among all beneficiaries or conduct studies requiring a large number of samples. Therefore, it is crucial to enhance our comprehension of managing mechanisms for CPRs by employing more sophisticated methods in addition to the existing empirical and field studies.

Agent-based models (ABMs) offer an attractive alternative to traditional methods (Gharakhani et al., 2022). One key advantage is their ability to design virtual experiments with more adaptable conditions than those in lab settings. Additionally, ABMs facilitate the examination of long-term dynamics in contrast to field studies (Poteete & Welch, 2004). These models allow for the creation of complex simulations that capture the influence of numerous factors on participatory governance of CPRs. Consequently, the results can be compared to empirical findings, enabling the testing of the model's ability to reproduce observed patterns and dynamics in the real world.

Numerous studies highlight the importance of cooperation among different actors, such as water usage associations (WUAs) and NGOs, in modern irrigation systems, as opposed to autocratic policies implemented by a single authority, such as dam construction and inter-basin water transfers (Meinzen-Dick, 1997; E. Ostrom, 1992; Shivakoti & Ostrom, 2003a; Vermillion, 1997). Many of these studies confirm the potential for social cooperation in irrigation systems (Bardhan, 2015; Boyd et al., 2003; Janssen & Ahn, 2006; Janssen & Baggio, 2017; Janssen & Rollins, 2012; Elinor Ostrom & Gardner, 1993). However, further research is needed to understand the mechanisms of cooperation and the institutional, social, and cultural systems associated with it. Existing studies on irrigation governance mainly focus on theoretical analysis, field studies, and statistical methods, lacking the analysis of evolutionary trends and factors that influence the formation and self-organizing distribution of irrigation. The incorporation of interdisciplinary methods and advanced scientific tools, such as ABMs, can fill these gaps.

Cooperation among farmers in utilizing irrigation systems can stem from social interactions (Janssen & Baggio, 2017; Shivakoti & Ostrom, 2003b). To enhance our understanding of participatory water governance, we conducted a series of surveys targeting farming families. These surveys had two main objectives: firstly, they helped identify crucial factors influencing the development and design of behavioral mechanisms towards participation in the establishment of LIS; and secondly, they generated data for model calibration. From 2017 to 2018, we conducted field studies in villages located in Isfahan province, where water shortages for agriculture were prevalent. We collected general village data through questionnaires administered by village councils, assessing a total of 223 villages.

By adopting the approach of ABMs, this study explores the behavioral mechanisms underlying the formation of cooperation in establishing LIS. Understanding the cognitive, institutional, and social processes involved in self-organizing irrigation is challenging when it comes to collecting high-quality data for statistical analysis. ABMs offer a valuable framework for formulating hypotheses regarding rules or behavioral mechanisms, such as social learning (learning from others within a similar social group), which may not be directly observable or require indirect observation. These hypotheses can be effectively tested through simulations (Conte & Paolucci, 2014).

We conducted a comprehensive data collection process to gather detailed socio-economic information about farming families. This included data on various factors such as the size of farmer populations (group size), the total area of farmlands, the educational background of family heads, and specific data related to the use of irrigation systems by these families. We examined factors such as their access to water resources, the cost involved in participating in the collective use of LIS, and the extent of government grants received. In this study, our primary focus was on the affective factors influencing cooperation within the context of LIS. These factors encompassed group size (number of farmers), the level of government financial support (subsidy ratio to the total cost of LIS establishment), the role of different pioneer groups (those who encourage farmers, including individuals with higher education, stronger social relations (High degree), closer proximity to pumping water (Close owners), and a high level of agreement (High aggregate)), as well as neighborhood effects (random and scale-free social networks).

Various individual, geographical, social, and economic factors influence the transition from traditional irrigation systems to LIS and shape collective action towards this change. Identifying these factors and aligning policies accordingly is a fundamental approach for gaining farmer acceptance of LIS. The significance of identifying and understanding these factors and their level of influence cannot be understated, particularly in Isfahan province, which currently faces a water crisis due to its unique climate conditions. The negative consequences of this crisis include reduced crop and garden productivity, a significant decline in groundwater levels, land subsidence, water resource salinity and lower quality, environmental degradation, destruction of natural areas, and rural-to-urban migration. Consequently, participatory management of groundwater resources and the adoption of modern irrigation systems in Isfahan's villages hold immense importance. This study aims to address the following questions:

- Which pioneer groups within the social networks can effectively encourage farmer participation in LIS construction?
- How does the government's financial support level impact participation rates in LIS construction?
- What is the influence of group size on participation rates in the construction of LIS?

This study aims to provide valuable insights to help governments prioritize their limited financial resources for LIS development.

Although the focus of this study has been specifically on the participatory management of groundwater in the form of cooperation in the construction of a

LIS, the proposed model holds potential for broader applications. It can also be adapted to other common resources that rely on financial participation of stakeholders for their sustainability.

This study is organized into six sections. After the introduction, in section 2, theoretical and experimental literature on CPR and participatory conservation projects are reviewed and at the end of this section, the research gap in the area of common water resources will be presented by classifying the previous studies. Section 3 provides the research pattern within the framework of ABMs. In section 4, the sustainability of the proposed model will be analyzed. The role of each factor affecting the construction of LISs is discussed in section 5 and different scenarios are tested. And finally, concluding remarks and suggestions are provided in section 6.

2. A Review of the Related Literature

To comprehensively understand and analyze participatory management within the context of collective management, it is essential to explore two key areas of scientific literature: CPR and the history of protected areas. Groundwater is classified as a CPR, which refers to shared natural or man-made resources among different users (Asafu-Adjaye, 2000; E.Ostrom, 1992). Natural CPRs, such as forests, grasslands, fisheries, atmosphere, and groundwater, exhibit characteristics of both private and public goods. They are highly reducible and non-excludable. These characteristics have attracted significant research attention regarding the management and utilization of such resources (Agrawal, 2001; Fischer et al., 2004; Galinato, 2011; Heikkila et al., 2011; Janssen et al., 2015; Kapur, 2002; Sarker et al., 2008; Sarker & Itoh, 2001; Vallino, 2014; Vélez et al., 2009). The discussion on CPRs originated with the influential 1968 paper by Hardin, known as the "tragedy of the commons." Hardin argued that when multiple individuals exploit the same resource driven by personal profit maximization, the inevitable result is the overexploitation of CPRs, leading to detrimental conditions for all involved. He proposed either distributing CPRs among members or entrusting them to the government (Gharakhani et al., 2022; Elinor Ostrom & Gardner, 1993). While Ostrom did not reject Hardin's theory, she believed that, in most cases, communities can effectively govern CPRs unless the resource is extensive, stakeholders lack relationships, individuals act independently, and the cost of changing conditions is prohibitively high (Madani & Dinar, 2012; Elinor Ostrom, 1998). The current literature widely accepts that, under normal circumstances, a community can foster collective action and achieve sustainable use of limited resources, ensuring they do not exceed carrying capacity and remain compatible with growth rates (Gharakhani et al., 2022; Vallino, 2014; Yang et al., 2012).

In the 19th century, two methods were used to address the tragedy of the commons: fencing (such as enclosing forest areas) and prohibiting harvesting (such as banning the digging of wells and use of groundwater in certain plains). The intention was to protect common resources by implementing physical barriers, such as fences, around them (West et al., 2006). However, over time, empirical evidence has revealed the limitations of this approach, particularly in developing countries. Many individuals in these regions rely on natural CPRs for their livelihoods, engaging in activities like agriculture, livestock farming, fishing, and logging. Environmental protection organizations have encountered challenges such as free-riding, illegal resource extraction by locals and outsiders, and a lack of enforcement. These problems have prompted the development of participatory management through participatory conservation projects. These projects involve engaging the local community as an institution in the management of protected areas, granting them certain rights to exploit the common resources. The objective is to promote and enhance both nature conservation and local economic development (Watkins et al., 2013).

Participatory conservation projects can be divided into two modes: design mode and discovery mode. In the design mode, non-local individuals identify a problem and design a solution. In these cases, the government often provides financial support to encourage local participation. On the other hand, in the discovery mode, outside individuals become aware that the locals have already devised a solution for their problem, and they subsequently assist the locals in legitimizing their solution (Gharakhani et al., 2022). The construction of LIS as a participatory conservation project falls under the design mode. In such projects, contrary to Hardin's perspective, the natural CPRs are not distributed among individual members or converted into public goods. Instead, following Ostrom's viewpoint, it is the locals who manage the commons through collective action (Cai & Xiong, 2017; Meinzen-Dick, 1997; E.Ostrom, 1992; Shivakoti & Ostrom, 2003a).

ABMs have been widely used in various domains of water management, including surface water management (Lin et al., 2019; Pouladi et al., 2019), groundwater management (Anbari et al., 2021; Castilla-Rho et al., 2015; Ohab-Yazdi & Ahmadi, 2018), urban water management (Koutiva & Makropoulos, 2016; Tourigny & Filion, 2019), and flood and aridity management (Dubbelboer et al., 2017; Wens et al., 2019). However, most of these models have primarily focused on the utilization of CPR, overlooking the aspect of non-utilization decisions. Building upon the existing literature, this study aims to develop a comprehensive structural and behavioral model by investigating the following aspects: a) the role of individual, environmental, economic, and social factors in the acceptance of LISs; b) the importance of local farmers' participation in participatory` conservation projects, considering the involvement of various stakeholders such as local farmers, pioneer groups, and the government. Additionally, the study aims to analyze the impact of variables influencing collective action, such as government financial support, different pioneer groups, group size, and various social networks, on the participation rate in the establishment of LISs for villagers in Isfahan province.

This model offers several key advantages. Firstly, it effectively captures the dynamic nature of farmers' decision-making processes in response to the opinions of their peers. By considering behavioral conflicts, the model provides valuable insights for the government regarding the allocation of budgetary resources among villagers. This allocation is based on a classification system that takes into account factors such as population size, the type of pioneer group involved, and the social network dynamics within participatory conservation projects.

3. The Study Model

The model presented here is implemented in Netlogo (Wilensky & Stroup, 1999), a software platform for agent-based modeling that has increasingly been used both for educational and research purposes in the areas of social and natural sciences (for example in (Railsback & A, 2021; Richtig et al., 2021; Wilensky et al., 1999)).

To explain the structure of ABMs, the standard protocol of Overview, Design Concepts, and Details (ODD) is used. This protocol is presented in three sub-sections: Overview section, Design concepts, and Details.

3.1 Overview section

3.1.1 Purpose

This study employs an agent-Based Modeling approach to develop a behavioral model for simulating participatory management between the government and villagers in Isfahan province, with the aim of establishing LISs. The traditional method of self-managing irrigation has proven to be unsustainable. To prevent the tragedy of the commons (Hardin, 1968), a small group of individuals seeking sustainable use of water CPRs propose cooperation in the management of irrigation resources. This group acts as the pioneer group within the framework of community cooperatives. Their cooperation involves providing a budget for the transformation of flood irrigation into LISs, as well as their maintenance and repair. In the LISs, all agricultural lands within a village are integrated and cultivated as a shared agricultural resource, although this may lead to some farmers expressing dissatisfaction. To encourage participation, the government announces that it will contribute a significant portion of the construction costs for LIS projects, under the label of rural development projects, on the condition that there is consensus on the integration of farmlands. This study aims to investigate the role of various factors that influence collective action, including group size, type of pioneer group, government financial support, and the type of social network, in promoting cooperation for the establishment of LISs, specifically focusing on pressurized irrigation. The ultimate goal is to achieve participatory management in the villages of Isfahan province, Iran.

3.1.2 Entities, state variables, and scales

There are three main agents involved in this research:

1.Farmers: This agent is further divided into two groups:

a. Ordinary farmers: Initially, they exhibit reluctance to participate and continue using flood irrigation methods.

b. Pioneer group: This small subset of farmers forms community cooperatives and proposes the establishment of LIS for the participatory management of groundwater. Their task is to convince other farmers to join and actively participate in the initiative.

2.Government: In this model, the government serves as a single entity responsible for providing subsidies to participants. Additionally, it has the ability to directly reduce the costs associated with cooperation.

3.Irrigation source: This represents the water collection and all the related infrastructure used for irrigation. All farmers are considered owners of this resource. Initially, unsustainable water extraction practices are observed, where all farmers extract the maximum amount of water. To address this issue, the construction of LIS becomes necessary for the participatory management of groundwater.

3.1.2.2 Characteristics of agents

Each farmer is defined by four distinct attributes, including the surface area of farmland (Farm), distance from the established water CPR (Distance), level of education (Education), and level of agreement with cooperation (Aggregate).

3.1.3 Process overview and scheduling

The process begins with a small group of pioneer participants from each village who take part in the construction of the LIS project. These farmers form community cooperatives. To facilitate cooperation, the pioneer group is categorized into four distinct groups based on the recommendations of the organization for rural cooperatives of Isfahan province:

- Close Owners: This group consists of farmers whose land is located closer to the water CPR and pumping systems. Their proximity results in higher land prices and better irrigation, without the need to deal with clogged pipes. The close owners are more motivated to convince other farmers to participate in the project due to these advantages.

- High Degree: This group holds the highest level of social interaction and is highly respected among other farmers, including members of the rural council and village elders. Their influential social connections enable them to effectively persuade others to participate.

- High Education: This group possesses a high level of education and is capable of analyzing the strengths and weaknesses of the LIS systems. They can calculate the costs and benefits associated with the project, and their expertise helps them convince other farmers to join.

- High Aggregate: This group is highly motivated to establish LIS because they cannot benefit from the current method of water withdrawal, either due to financial difficulties or having uncultivated lands as a result of aridity. Their motivation drives them to advocate for the project.

To determine the most suitable pioneer group for achieving a higher participation rate in establishing the LIS, it is important to consider the effectiveness of each group in different simulations. The economic decision-making behavior of each farmer is influenced by their mental indicators (Philippe Caillou et al., 2015), socio-environmental stimuli (Delre et al., 2007), and individual psychological characteristics (Aghaie et al., 2020; Roozmand et al., 2011).

The mechanism for farmers' membership in the cooperation is such that if the cost of the willingness to participate (Propensity) is lower than the participation fee (Fee), the farmer becomes a potential participant. Above all, the decision of farmers to become actual participants is highly influenced by neighborhood effects.

3.2 Design concepts

The cost of a farmer's propensity to participate (Propensity) is directly proportional to the surface area of their farmland (Farm) and inversely proportional to the distance from the pumping source (Distance). This mental indicator is mathematically represented by Equation 1, which calculates the ratio of the farmland surface area to the distance from the pumping source. It is important to note that this index remains constant throughout the entire simulation process.

$$propensity_i = Propensity\_Cof * \frac{farm_i}{distance_i} \qquad (1)$$

The propensity coefficient is a fixed value for all farmers within a village but varies across different villages, influenced by environmental factors such as the EC water index, agricultural land fertility, and well depth. For instance, the coefficient is directly related to an increase in well depth, as it raises the individual cost of water extraction. Conversely, the coefficient exhibits an inverse relationship with the EC level of the water, as higher levels can result in sedimentation issues within the pressurized irrigation system.

The total cost of establishing the LIS (Cost) is influenced by all the participants (num_adp). As the number of participants increases, the irrigation system requires more pumping stations and additional pipes, resulting in higher establishment costs. However, due to economies of scale, the increase in total cost occurs with a decreasing slope. The proposed function for the total cost of LIS establishment can be described as an ascending exponential function with a descending slope, as represented by Eq.2:

$$cost_t = num\_adp_t^{\,cost\_power} \qquad 1 < cost\_power < 1.5 \qquad (2)$$

If the outcome of the interactions between farmers leads to a consensus on establishing the LIS, the government will contribute a portion of the expenses through participatory conservation projects. The expense share of participation (Fee) for each farmer is calculated by dividing the total cost not covered by the government by the number of participants, as described in Eq.3:

$$fee_t = \frac{(1-subsidy\_ratio)\times cost_t}{num\_adp_t} \tag{3}$$

The Subsidy_ratio represents the proportion of the total cost of establishing the LIS that is covered by the government as financial support. The number of participants has a dual effect on the expense share in the establishment of the irrigation system. On one hand, it increases the total cost of establishment, but on the other hand, it distributes the cost unpaid by the government among more individuals. However, due to economies of scale, as the number of participants increases, the share borne by each person decreases.

An economically justified scenario for a farmer to participate in the LIS establishment occurs when the fee paid by the farmer is lower than the cost of their propensity to participate. In such cases, the farmer becomes a potential participant.

$$if\ \ fee_t < propensity_i \rightarrow potential\, participant \tag{4}$$

Farmers base their decisions on imitating the average opinions of their neighbors, as noted in previous studies (Sivapalan et al., 2012; Di Baldassarre et al., 2013; Viglione et al., 2014). As a result, each potential participant engages in negotiations with other farmers who have frequent interactions to reach a final decision and transition from potential to actual participant.

The agreement level of each farmer (Aggregate) represents the likelihood of a potential participant becoming an actual participant. The aggregate of a potential participant is updated by taking a weighted average derived from the aggregates of other farmers who interact with them:

$$aggregate_{it} = \frac{\sum_{j=1}^{m} farm_j \times aggregate_{jt}}{\sum_{j=1}^{m} farm_j} \tag{5}$$

The update of the aggregate for potential participants can have an impact on the aggregate of new participants, forming a network. This complexity in the updated aggregate is known as the neighborhood effect, which can be influenced by the type of social network.

In the graphical representation, when a potential participant transitions into an actual participant, their color changes from yellow to red. However, if the negotiation has a negative effect on an individual, the potential participant will exit the cooperation, and their color will change to green.

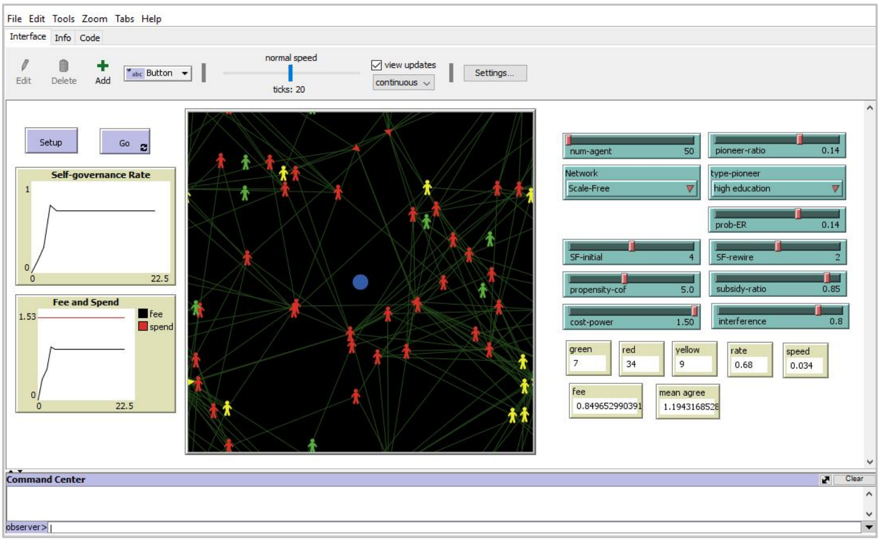

Figure 1. Graphical representation of simulating participation rate in cooperation to establish LIS

Source: *Netlogo software*

Farmers who choose to defect will face social punishment as a consequence of their unstable decision-making. In the subsequent round, these farmers will be excluded from the social network and the decision-making process by other farmers.

Ultimately, if more than two-thirds of farmers become potential participants, a consensus is reached in the decision-making process, leading to the integration of farmlands and the guaranteed establishment of the LIS. However, if, during the government's specified period[1], less than two-thirds of farmers participate as actual participants, a consensus for the establishment of the LIS has not been achieved, and the government will withhold subsidy payments.

$$\begin{cases} if num\_adp > \frac{2}{3} \times num\_agent and ticks < 20 \rightarrow collective action \\ if num\_adp < \frac{2}{3} \times num_{agent} and ticks > 20 \rightarrow no collective action \end{cases} \quad (6)$$

[1] 20 months (Refer to section 4-1)

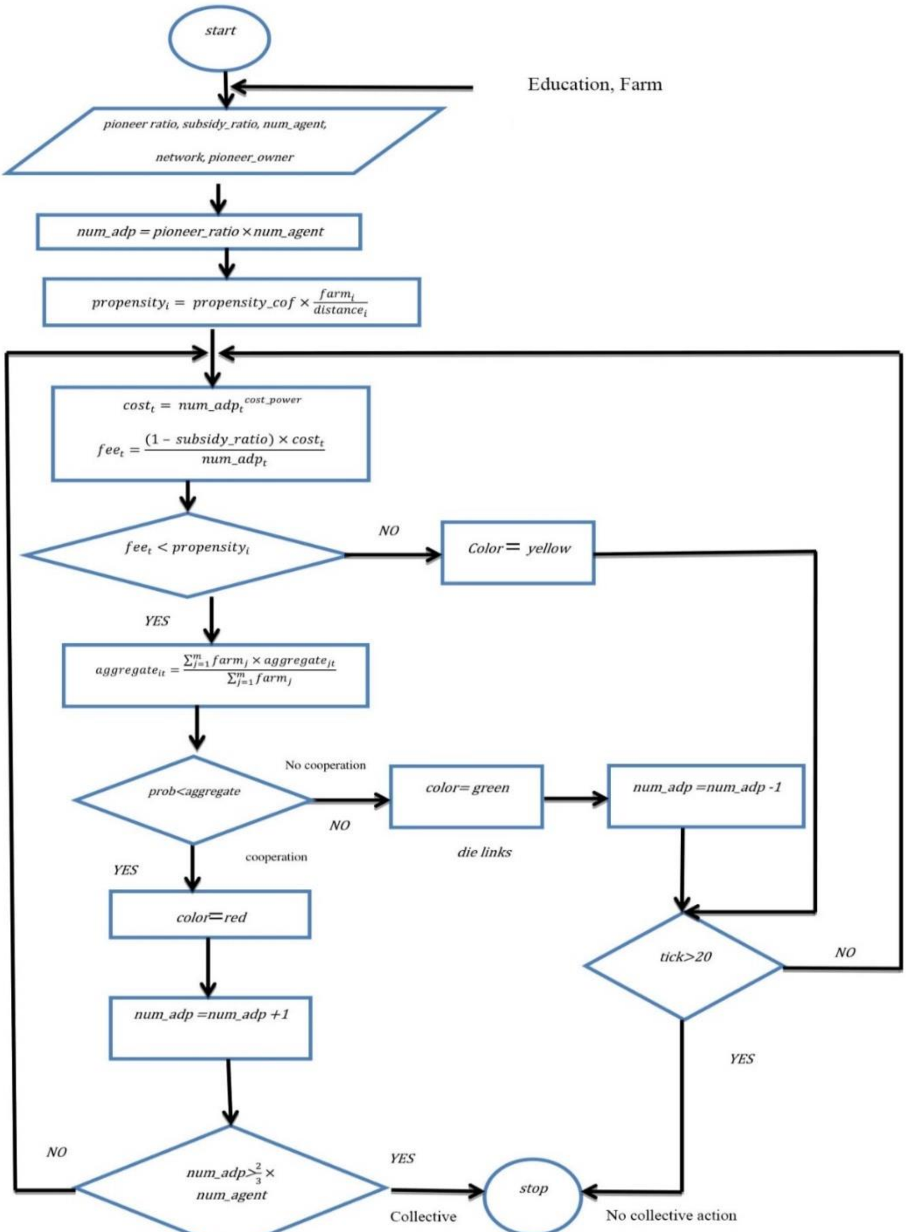

figure2. conceptual model
Source: *outputs of Netlogo software*

3.3. Details

3.3.1. Emergence

The model reveals the emergence of various effects as a result of farmers' collective actions in the construction (or lack thereof) of the irrigation source. Collective action represents an approach to the sustainable use of water Common Pool Resources (CPRs), achieved through the participation of farmers in the collective utilization of the irrigation source. However, when there is a low rate of participation among farmers, the collective action may not emerge.

3.3.2 Adaptation

In each iteration, every farmer outside the LIS updates their decision regarding participation or non-participation. This decision is influenced by factors such as the financial share in the construction of the LIS and the level of agreement with other farmers who interact with them.

3.3.3 Learning

Farmers are constantly interacting with their neighbors and updating their agreement with LIS construction.

3.3.4 Objectives

The agents' objective is to choose between flood irrigation and LIS, taking into account social and economic issues. The government's goal is to prioritize villages to allocate the limited financial budget to construct a LIS.

3.3.5 Prediction

In this model, farmers do not engage in predictive behavior.

3.3.6 Sensing

Farmers are aware of which fellow farmers in their village have participated in the cooperation.

3.3.7 Interaction

In this study, social interactions among farmers are facilitated through a social network. The structure of the network can influence the level of cooperation in collective action scenarios (Gould, 1993). As empirical data on farmers' social interactions is lacking, graph theory is employed to represent a realistic network. Theoretical graphs used in this research include random and scale-free social networks.

Random networks are typically created using the Erdős–Rényi model (Erdős & Rėnyi, 1959). In this model, a fixed probability is assigned to each potential edge independently of the other edges. On the other hand, scale-free networks display a structure where a majority of vertices have few connections while a small number of vertices are highly connected. The Barabási and Albert model is commonly used to develop scale-free networks. This model employs preferential attachment, meaning that vertices with a higher degree have a greater probability of forming new connections with other vertices (Gharakhani et al., 2022, Mohammadi et al., 2024; Barabási & Albert, 1999).

3.3.8 Stochasticity

The spatial distribution of farmers in terms of their coordinates x and y follows a normal distribution. Additionally, the distance of farmers from the irrigation source, which reflects their dependence on the source, is also stochastic. The initial value of the farmers' aggregate for the establishment of the LIS is stochastically distributed among farmers, following a continuous uniform distribution within the [0, 1] interval. Furthermore, the characteristics of farmers, such as the surface area of their farmland and their level of education, are modeled with a Poisson probability distribution. The average values for these characteristics are derived from field data collected in villages of Isfahan province.

3.3.9 Collectives

All farmers in the model belong to a village and are on the villages' social network. There are no other collectives in the simulations.

3.3.10 Observation

The model provides an observation based on expanding cooperation in the establishment of LIS. How the number of participants changes over the time is represented as diagrams.

3.3.11 Initialization

To execute this model, a network of farmers is generated, representing their relationships, characteristics, and their connection to the irrigation source. By utilizing the corresponding sliders, the parameters can be adjusted, allowing for sensitivity analysis. The range of adjustment for the model sliders is determined based on the variation observed in the statistical data from villages in Isfahan province.

3.3.12 Input

This model doesn't contain any input from external sources.

3.3.13 Sub-models

ABMs utilize stochastic probability functions to initialize certain variables related to agent features and strategy selection. This is necessary when some information is unavailable or obscured. However, the application of these stochastic functions within a complex socio-economic system can impact the sustainability of the model results. Therefore, it is crucial to examine the statistical significance and stability of parameter signs in the model outputs to validate the model before addressing the research questions. This validation process involves conducting multiple simulations using various combinations of parameter states and model outputs (such as the rate of actual participants). To analyze the results, a cross-sectional regression is employed:

$$\frac{red}{num\_agent} = \alpha + \beta_1 * subsidy_{rate} + \beta_2 * propensity_{cof} + \beta_3 * pioneer\_ratio + \beta_4 * cost\_power + u_i \quad (7)$$

The cross-sectional regression analysis is conducted with the dependent variable representing the rate of actual participants. The explanatory variables consist of the share of government subsidies in the total costs of LIS establishment, the coefficient of the propensity function, the initial ratio of the pioneer group to the total number of farmers, and the power of the total costs function. To address the research question, a simulation is performed by manipulating the parameter sliders and examining the impact of each variable on the rate of cooperation.

3.3.14. Run

The simulation was conducted using NetLogo software (version 6). By adjusting the sliders to different parameter states, a total of 65,000 simulations were conducted, with each simulation treated as an observation for the regression analysis presented in Section 3.3.13. To convert the graphical data from NetLogo into numerical data, MATLAB software (version 13) was utilized. Additionally, EViews software (version 9) was employed to estimate the regression model, and the results are reported in the subsequent sections.

4. Empirical Results

In this research, by using agent-based simulation for a hypothetical society, various conditions that can happen in a society have been created so that the problem related to the data can be reduced to some extent. It is important to note that the outcomes of agent-based simulations can vary across different runs. Therefore, to ensure more reliable analysis, it is recommended to examine the variation in output results by conducting multiple executions (Mohammadi et al., 2024; Van dam et al., 2012). For this study, 4000 repetitions were utilized to run the model under different modes, enabling a more robust analysis of the results.

Section 4.1 presents the descriptive statistics table of the variables and the histogram depicting the participation rate of farmers. In section 4.2, regression estimation and relevant classical hypothesis tests are provided. Finally, in section

4.3, the impact of group size and government financial support under different scenarios is illustrated graphically.

4.1. Descriptive statistics and participation rate histogram

Table 1. Descriptive statistics of simulation's variables

	Subsidy_Ratio	Participation_rate	Propensity_Cof	Cost_Power	Pioneer_ratio
Mean	0.499609	0.475000	5.499615	1.250177	0.150180
Median	0.500000	0.427658	5.000000	1.300000	0.150000
Maximum	1.000000	1.000000	10.00000	1.500000	0.200000
Minimum	0.000000	0.000000	1.000000	1.000000	0.100000
Std. Dev.	0.273370	0.257481	2.868852	0.170811	0.031604
Skewness	0.000576	0.252596	0.000732	0.006288	0.007765
Kurtosis	1.797423	2.659159	1.783167	1.730459	1.782005
Jarque-Bera	3916.775	0.811226	4010.187	4365.540	4018.500
Probability	0.000000	0.666568	0.000000	0.000000	0.000000
Observations	65000	65000	65000	65000	65000

Source: *outputs of EViews software*

According to the table of descriptive statistics, the Kurtosis of all variables is below 3, indicating that their distributions is shorter than the normal distribution. According to Skewness, all variables` distribution are right-leaning.

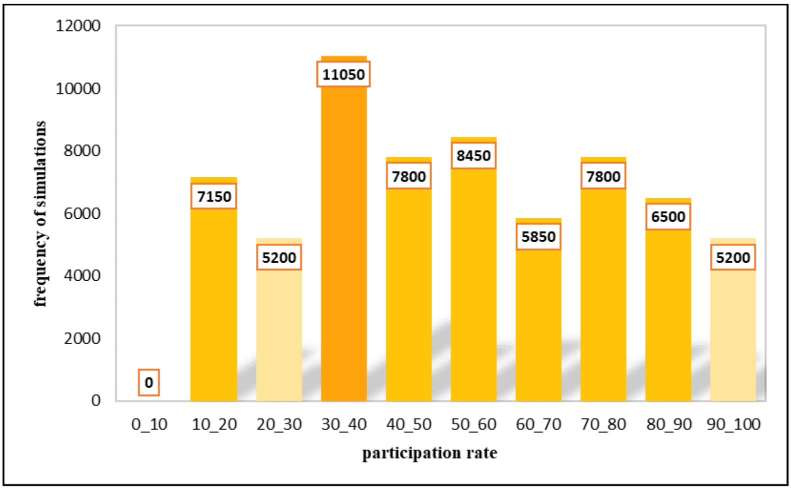

Figure 3. Histogram of frequency of farmer's participation rates
Source: *outputs of Netlogo software*

Figure 3 illustrates the distribution of farmer's participation rates in the construction of the LIS system, as generated by the research model. The data indicates a well-dispersed pattern. The highest column, representing the 30-40 participation range, corresponds to 11,050 simulations (17%). Additionally, fewer than 5,200 simulations (less than 10%) were completed with full farmer participation. These findings demonstrate that the research model's simulation configuration encompasses various scenarios. Furthermore, the choice of a 20-time-period (months) stopping point adequately captures this range of possibilities.

The reason for the zero frequency of simulations in the range of 0 to 10% for the farmers' participation rate is due to the fact that in this research, a proportion of farmers are considered as the pioneer group, who always hold an opinion on participation, and in this research, their Pioneer_ratio is considered to be more than 10% of the population of farmers.

4.2. Model validation

The results of the model estimation are presented in Table 1. The estimation takes into consideration various combinations of social networks and pioneer groups.

Table 2. Results of estimating sustainability regression by ordinary least square method

Variable	Coefficient	t-Statistic	Prob.
C	0.737587	189.8807	0.0000
Subsidy_Ratio	0.530725	341.7443	0.0000
Propensity_Cof	-0.294884	-21.95057	0.0000
Pioneer_Ratio	0.050984	344.5210	0.0000
Cost_Power	-0.648862	-261.0754	0.0000
R-squared	0.823319	Mean dependent var	0.427658
Adjusted R-squared	0.823308	S.D. dependent var	0.257481
F-statistic	75717.88	Durbin-Watson stat	2.014625
Prob(F-statistic)	0.000000		

Source: *outputs of EViews software*

At a 95% confidence level, the table above reveals that in all generated states, the share of financial support provided by the government in the total establishment costs and the initial ratio of the pioneer group to the total number of farmers have a statistically significant positive effect on the rate of cooperation. Conversely, the coefficient of the propensity function and the power of the exponential function of total costs have a statistically significant negative effect on the rate of cooperation. These findings are consistent with expectations and can be utilized to create different scenarios.

The tests related to the classical hypothesis for the regression of farmers' participation rate are reported in table 3:

Table 3. Examining the types of classical hypothesis for the regression of participation rate of farmers

Test	Test Type	Value	Probability	Status
Normality	Jarque-Bera	0.8112	0.6665	The acceptance of the H0
Heteroskedasticity	Breusch-Pagan-Godfrey	2.2355	0.0684	The acceptance of the H0
Model Specification Test	Ramsey Reset Test	2.8083	0.0971	The acceptance of the H0
		Variables	Uncentered VIF	
Multicollinearity	Variance Inflation Factor	Subsidy_Ratio	4.340541	Low Evidence of Multicollinearity
		Propensity_Cof	6.986815	
		Pioneer_Ratio	4.675609	
		Cost_Power	3.329050	

Source: *outputs of EViews software*

Based on the classical hypothesis at a 95% confidence level, the results indicate the following:

- The Jarque-Bera test demonstrates that the distribution of regression residuals follows a normal distribution.
- The Breusch-Pagan-Godfrey test indicates no heterogeneity of variance.
- The Ramsey-Reset test confirms that the chosen regression functional form is appropriate.
- The multicollinearity test between the independent variables reveals low evidence of multicollinearity.

Consequently, based on these results, the estimated coefficients presented in Table 2 are considered BLUE[1] (Best Linear Unbiased Estimators).

4.3. Scenario-making

To analyze the average trend of influential agents in the rate of cooperation for LIS establishment, two factors were considered: the share of financial support provided by the government (subsidy_ratio) and the group size (num_agent). The

[1] Due to the high number of observations, the t-statistics and R2 of the regression are high. It is not due to the lack of classical hypothesis.

respective sliders were adjusted over 20 ticks (ticks=20), and the results are depicted in figures 4.a and 4.b. The simulations were differentiated based on various pioneer groups and social network structures.

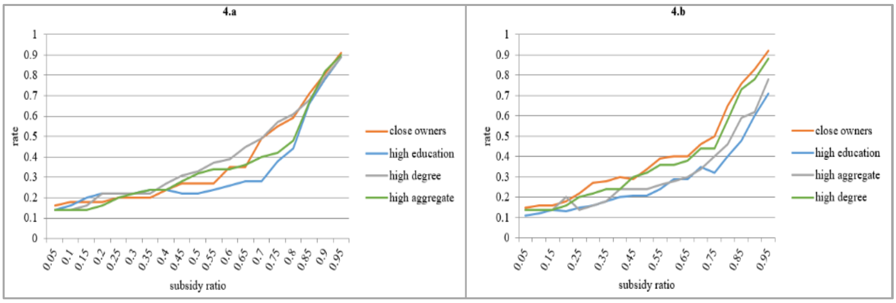

Figure4. effect of government financial support on the rate of cooperation in different pioneer groups; (a) in random social network (b) in scale-free social network
Source: *outputs of Netlogo software*

The result of figure 4 demonstrate that regardless of the type of pioneer group and social network, a higher share of financial support from the government for LIS establishment corresponds to a higher rate of farmer participation. For instance, if the government's financial support covers more than 85% of the total construction costs for LISs, an average of approximately 67% of farmers in each village of Isfahan are expected to cooperate in the participatory management of groundwater resources. Furthermore, the simulation results reveal that in a scale-free social network, regardless of the government's financial support level, the Close owner group exhibits the highest rate of cooperation and diffusion speed compared to other pioneer groups. In contrast, in a random social network, no significant differences are observed among pioneer groups. This finding suggests that in collective actions, individuals with higher education are less likely to be accepted as pioneer group members by farmers.

This finding aligns with the findings of Cai and Xiong (2017), which suggest that government financial support can assist farmers in reducing entry barriers and cooperation-related costs. However, it contradicts studies such as Watkins et al. (2013), which propose that government interventions, particularly through the establishment of laws and regulations, may weaken incentives for collective action. For instance, the government may implement rules and regulations concerning water resource utilization and distribution in the region, which could impose restrictions on farmers' water usage and require compliance with specific regulations. These limitations and adjustments may potentially diminish farmers' motivation to engage in cooperative efforts.

The simulations run to analyze the role of group size in the rate of cooperation and speed of diffusion are depicted in figures 5.a and 5.b.

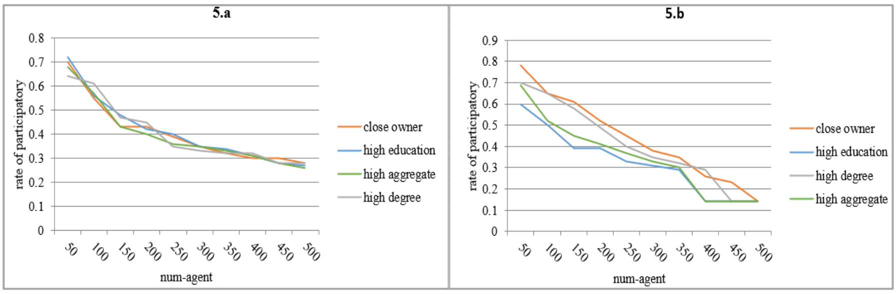

Figure5. effect of group size and rate of cooperation in different pioneer groups; (a) in random social network and (b) in scale-free social network

Source: *outputs of Netlogo software*

The results indicate that irrespective of the pioneer group and social network structure, an increase in the number of farmers leads to a significant decrease in both cooperation levels and the speed of dissemination. It is important to note that the group size has two economic and social effects on the participation rate. On one hand, as the group size increases, the individual's cost share decreases due to economies of scale, making participation in cooperation economically viable for farmers. On the other hand, a larger group size fosters greater diversity of opinions, which can diminish the participation rate. Consequently, based on the simulation output, it can be inferred that although the number of potential participants rises with an increase in the number of farmers, many of these potential participants will not actually engage in cooperation due to conflicting opinions. This implies that as the number of farmers grows, the negative influence of the social component outweighs the positive impact of the economic component, leading to a decline in the cooperation rate. This finding aligns with the perspectives of Ostrom (1992) and Olson (1971), who consider group size as a hindering factor in collective action. It contradicts studies such as Oliver and Marwell (1988) and Gintis (2014), which argue that larger groups possess a greater number of members with diverse skills and expertise, thereby enhancing their ability to mobilize financial and human resources.

5. Discussions

The findings of this study emphasize the significance of government financial support in fostering cooperation for the establishment of LISs. A higher rate of government support enhances farmers' participation in cooperative efforts. Specifically, if government subsidies cover more than 85% of the total costs of LIS establishment, an average of approximately 67% of farmers in each village in Isfahan province are likely to cooperate. This finding aligns with the results of field studies, which indicate that successful participatory conservation projects in Isfahan province have received support from the Agriculture Organization (Jihad). These supports encompass direct and indirect subsidies, as well as the granting of proprietary rights to irrigation infrastructures.

However, it is important to note that when these financial supports conflict with the farmers' ownership independence from the government, they can impede cooperation or even discourage farmers from engaging in collective action for agricultural measures. For example, the construction of the First Meidanak dam in the west of Isfahan resulted in the abandonment of 700 hectares of cultivated farmlands. To ensure better performance and sustainable development of irrigation systems, the government should consider limiting direct financial support to LIS facilities in villages with smaller populations and instead focus on long-term policies such as technical training, public services, and improving the livelihoods of the local community (Yang et al., 2012).

Furthermore, the size of the group can act as a deterrent to cooperation among Isfahan villagers in the establishment of LISs. Regardless of the pioneer group and social network, a larger number of farmers in a village corresponds to a significantly lower rate of cooperation and diffusion speed, making collective action less likely. This could be attributed to the increased potential for conflicts and difficulties in reaching agreements as the number of farmers rises. Moreover, variations in farmland fertility can lead to opposition and resistance towards integration. Field studies have revealed instances where populated villages in the east of Isfahan have transformed their farmlands into garden villas, rendering integration and collective action impractical. Similarly, in the western region, outsourcing of farmlands has been observed in the Buin and Miandasht areas. Olson, in his book "The Logic of Collective Action," posits that groups consist of both wise and self-seeking individuals, whereby larger groups tend to have more members who seek to benefit from the efforts of others without contributing equally. Consequently, as the group size increases, the challenges of attaining collective benefits become more pronounced.

Social networks and pioneer groups are additional factors that influence collective action and the speed of diffusion. In a random social network, where individuals have nearly equal social status, the primary factor that encourages farmers to participate is government financial support. In this study, we did not find any significant evidence indicating the importance of the pioneer group type in a random social network. One reason for this could be that the influence of neighborhood connections is negligible compared to the impact of government financial support. Therefore, the ability to afford the costs of cooperation becomes the primary limitation for farmers' agreement in a random social network. Another reason could be the relatively low heterogeneity among families, which makes it difficult to distinguish the effects of personality and social status when selecting a pioneer group. This observation holds true in real-world scenarios as well. For example, in the villages of the Lanjan region, households are relatively homogeneous in terms of their reliance on irrigation. They all make a living through rice cultivation and face significant poverty. In such villages, cooperation is highly influenced by government support, with less dependence on the socio-economic attributes of households.

In contrast, in villages with social relations based on a scale-free social network, they can play a superior role in encouraging other farmers to participate. This has been observed in various instances, such as the integration of 30 wells and the transition to pressurized irrigation in Nasrabad, Mahyar Plain (located in the east of Isfahan), the integration of 350 hectares of pomegranate gardens and the utilization of Qanat in Jalalabad region, Najafabad, and the integration of water wells in Nikabad, Jarqooyeh Sofla District.

In conclusion, if we replace the surface area of farmland (Farm) with other variables such as household size or the built-up area of residential houses, this model can be extended to measure cooperation in the provision of club goods, such as water and gas supply systems, for the management of natural resources.

6. Conclusions

This study aims to design a fundamental framework that explains the participatory management of groundwater through cooperation among farmers within a village to establish of LIS (Local Irrigation Systems). An agent-based simulation model was developed based on the cooperative process that would emerge from this framework to achieve this objective. Using local community data obtained from a sample of 223 villages in Isfahan province, the model was employed to investigate the effects of group size and government financial support, taking into account different types of pioneer groups and social networks, on the participation and diffusion speed among local farmers.

After examining cooperation expansion procedures in the real world and in existing literature, it becomes apparent that farmers' decision-making process is influenced by various socio-economic factors. From an economic perspective, a farmer becomes a potential participant when the cost of joining the cooperative effort is outweighed by their share in the expenses of establishing the LIS (Local Irrigation System). In simpler terms, cooperation becomes economically viable for a farmer when it is justified for them. The likelihood of a potential participant transitioning into an actual participant is directly proportional to their level of agreement with the implementation of the participatory conservation plan. This degree of agreement is constantly influenced by neighborhood effects. Therefore, even if the economic feasibility exists, there is a possibility that a potential participant may refrain from participating in the establishment of the LIS due to the unfavorable opinions of other farmers they interact with.

Field studies conducted in the villages of Isfahan province reveal that the cost of engaging in cooperative efforts varies depending on the socio-economic conditions of each village. In villages where water resources are scarce, cooperation levels tend to be lower if the establishment of an LIS is expensive due to inadequate infrastructure. As cooperatives operate as non-profit organizations, they often face financial challenges. Therefore, the provision of financial support by the government plays a crucial role in facilitating the expansion of cooperation for the construction of LIS.

The government's provision of direct subsidies as the sole measure can easily create a dependency on government support among farmers. Additionally, certain government projects can have detrimental effects on irrigation systems, undermining their effectiveness (Shivakoti & Ostrom, 2003a). Therefore, it is essential to understand the self-organizing mechanisms of LIS to mitigate the adverse effects of government intervention (E. Ostrom, 1992). Within this framework, granting proprietary rights of irrigation systems to local farmers and establishing a clear definition of their legal position within the LIS becomes crucial for the long-term sustainability of the irrigation system. As recommended in the World Development Report (1994), empowering users and other stakeholders by giving them a strong voice and real responsibility can enhance the economic benefits of investment in small to medium projects aimed at building social capital.

For government policies to be effective, it is crucial to consider both the environmental structure and the social interactions among farmers (Britz et al., 2013; Yang et al., 2012). To prioritize financial support, the government should take into account both the size of the farmer groups and the topological structure of the social networks in which cooperation takes place. Based on the simulation results, it is found that in less populated villages, there would be a higher probability of collective action in establishing LIS. Therefore, it is recommended that the government initiate its financial support in these villages. Furthermore, in villages with a scale-free structure of social networks, priority should be given to the Close owners.

We should mention that we are at the beginning of the modeling process of the participatory management of groundwater. However, numerous factors can be incorporated to further develop the model. For instance, one potential addition could be the simultaneous management of surface and underground water resources. In such a scenario, aspects such as water rights and the efficiency of government allocation for surface water could also be integrated into the model. It is worth mentioning that our current study can be served as a foundational model, providing a framework for future researches.

Author Contributions

Conceptualization: all authors; methodology: Sasan Gharakhani; validation: Dr. Hadi Amiri and Dr. Babak Safari; formal analysis: Sasan Gharakhani; resources: Maede Mohammadi; writing—original draft preparation: Sasan Gharakhani and Maede Mohammadi; writing—review and editing: Maede Mohammadi; supervision: Sasan Gharakhani and Maede Mohammadi. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

No external datasets were used in this study. The results were generated through software simulations and analyses.

Acknowledgements

Not applicable

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