Narrative Documentation of

A Distributed Socio-Hydrological Framework for Integrating Perception and Groundwater Dynamics in Farmers' Crop Choice Modeling

Zahra Soleimanzadeh

Azadeh Ahmadi*

*Corresponding author’s e-mail: az_ahmadi@sbu.ac.ir

1. Purpose

This study aims to simulate the decision-making process regarding cultivation patterns by developing an agent-based model. In this model, the anthropogenic and mutual impacts of farmers' agricultural activities and water table fluctuations have been investigated. This approach ensures that groundwater management policies considered by the authorities in charge are aligned with the preferences and concerns of agricultural farmers within the study area. This alignment between extraction limitations and agricultural performance procedures can enhance farmers' alignment and compliance with regulatory policies. This approach is designed to help the authorities to control the agricultural water consumption of farmers by a better understanding of their behavioral patterns.

2. Entities, state variables, and scales

In this study, the number of simulated agents, including agricultural farmers, is 1724, and the behavior of other agents, such as orchard farming, industries, services, and domestic use, has yet to be considered. The authorities in charge in the area change the water extraction limitations according to groundwater depth, which indirectly controls the behavior of farmers. Still, these agents have not been simulated in the model. In the present model, the decision-making process of agricultural farmers is simulated as autonomous, semi-logical agents selecting cultivation patterns based on their psychological and individual attributes within an agent-based modeling framework. Initially, senior managers define the constraints on farmers' groundwater extraction based on current groundwater depths, standard water depths, and maximum water depths in the defined area. This approach allows for simulations of interactions between policymakers and agricultural farmers, with feedback on management decisions.

The social model is executed annually to calculate pumping rates in extraction wells, while the hydrological model runs monthly, calculating monthly water tables. This study's environment is the Isfahan-Borkhar aquifer's shape, divided into 90601 patches in the NetLogo environment. This aquifer, with an area of 1602.8 square kilometers, is an unconfined aquifer located in Iran's arid and semi-arid central region.

Table 1 specifies the types of parameters affecting the components that shape human behavior. All parameters in the structural equation of the theory of planned behavior are quantified between zero and one. By identifying the factors that influence perceived behavioral control among farmers regarding changing crop patterns and reducing water consumption, the numerical value of the specified parameters is measured on a scale from zero to one, where zero indicates the least and one the greatest amount. Additionally, the environment has been introduced to the model by incorporating the shape file of the aquifer. The boundaries of this simulation are limited to this case study.

Table 1. Components influencing the structural equation in the theory of planned behavior

Parameter type	Type	Psychological components	Social component
Dynamic	Economic	Welfare Level	Attitude (A)
Static	Psychological	Trust in Authorities	
Static	Psychological	Farming Experience	
Static	Psychological	Education Level	Social Norm (SN)
Static	Psychological	Understanding of Subsidence Consequences	
Dynamic	Environmental	Groundwater Status	
Static	Psychological	Age	Perceived Behavioral Control (PBC)
Static	Psychological	Education level	
Static	Psychological	Farming experience	
Static	Psychological	Livelihood Dependence on Agriculture	

3. Process overview and scheduling

In this model, farmers first decide what crops they will cultivate based on their historical memory, which has been initialized in the model. Then, after deciding on the cultivation pattern, the pumping rates are distributedly calculated. At this step, the groundwater simulator runs to calculate monthly water tables because of changing initial conditions of hydrological parameters. Thus, state variables, including groundwater fluctuations and welfare levels, are updated monthly and annually.

The spatially distributed model considers the water availability constraints in wells based on groundwater levels, allowing for farmers' heterogeneous characteristics and decision-making conditions to be accurately represented. Consequently, the extent of resource constraints for each farmer corresponds to their agricultural water consumption management practices. Farmers acting as well exploitation representatives and decision-makers must decide on upcoming cultivation patterns based on their updated personal characteristics. Therefore, farmers must decide on their desired cultivation patterns for the next year based on their inclinations and assessments of water consumption constraints. This process continues through the simulation period, with annual updates to groundwater extraction limits and other dynamic parameters for farmers to consider in future decision-making.

4. Theoretical and empirical background

In a watershed, diverse stakeholders often have conflicting interests as they seek to exploit resources for their benefit. This variety and the resulting conflicts complicate water resource management for policymakers and managers worldwide. Groundwater, serving numerous individuals, organizations, and industries, exemplifies common resources and complex systems. Changes in this system can influence stakeholder behavior, while human consumption patterns can also impact the natural environment. Various modeling approaches have been developed to study these complex adaptive systems to explore the interplay between human and water subsystems.

Coupled human-nature systems (CHANS) provide a structured framework for simulating these interactions, with socio-hydrological models focusing specifically on water resource systems and their relationship with human agents. These models incorporate essential concepts such as dynamics, reciprocal effects, and heterogeneity in the human-water relationship. In addition to these theories governing water resources, in this model, farmers decide according to the theory of planned behavior, which is a psychological theory in estimating the willingness of agents to conduct a particular activity.

5. Individual Decision-Making

Farmers in this agent-based model decide on their cropping patterns. In fact, by considering several factors, including available water, intention towards water conservation, groundwater condition, and their behavioral group, farmers decide on what crop to cultivate for the simulation period. The authorities in this case study are not explicitly modeled but control the water consumption of farmers. In fact, before making any decisions, a farmer examines the available groundwater levels based on the constraints set by the authorities.

Farmer's behavior in this model is simulated based on the theory of planned behavior, which perfectly reflects the assumptions of the bounded rationality theory in the decision-making process. Additionally, this framework, inspired by TPB, comprehensively incorporates cultural patterns and social norms governing the case study, which can play a vital role in farmers' decisions. Each farmer peruses a specific objective in this study according to their behavioral group. For instance, for conservative farmers, minimizing water consumption can fulfill success criteria, while for active farmers, maximizing profit is a priority. Welfare level and groundwater condition are the most critical factors in shaping farmers' behavior. Thus, farmers mostly try to adapt their decisions to improve these parameters. One of the significant strengths and novelties of the present work is its high spatiotemporal resolution, as farmers' decisions and behaviors are influenced not only by the spatial heterogeneity of aquifer conditions, such as water levels but also by temporal variations in psychological parameters.

6. Learning

Despite heterogeneity in farmers' features and preferences over time and across space, their criteria for choosing their crop pattern do not change. The learning process has not been incorporated into this structure as the social simulator is inspired by the theory of planned behavior, which has not explicitly considered this process.

7. Individual sensing

One of the most influential factors impacting farmers' decisions is the welfare level, calculated based on the state variables, including net benefit and cultivated area assigned in the model. When the farmers make decisions, they compare their social status according to the average profit of the farmers in the case study. Thus, it is assumed that farmers sense this parameter on their own in this process. Moreover, when it comes to interactive farmers, they perceive the behavior and decisions of their neighbors and their welfare level to imitate their decisions. The environmental state variable that each agent will sense in making their decisions is the spatially and temporally dynamic groundwater condition. It has been assumed that agents know these variables and obtain this information, and the costs for cognition are not explicitly modeled in this model.

8. Individual prediction

In this model, agents are considered myopic. To clarify this point, when farmers want to make decisions, they consider the historical data and current groundwater conditions and cannot predict the upcoming conditions. However, their decisions can alter the future groundwater depth and force them to employ a particular strategy. The most crucial predictive parameter in this model is groundwater condition, which can induce farmers to reconsider their decisions and engage in unauthorized groundwater extraction to meet their water needs and continue their previous cultivation. More precisely, upon completing the decision-making process regarding the crop to be cultivated, the estimated profit from the chosen crop for some farmers, given the severe restrictions on groundwater extraction and the necessity for intense deficit irrigation, turns out to be negative. Consequently, these farmers, recognizing that their interests are at risk due to the reduced water availability, resort to non-compliant behaviors.

9. Interaction

Direct and indirect interaction among agents is considered. Farmers are classified into four behavioral groups by calculating each farmer's willingness to conserve water resources, each with different decision-making priorities. Farmers with a willingness score between 0 and 0.25 are categorized as active farmers, having the slightest inclination towards water conservation. Interactive farmers have a willingness score ranging from 0.25 to 0.5. Farmers fall into the semi-perceptive category if their willingness score is between 0.5 and 0.75. Finally, perceptive farmers, who are most willing to conserve agricultural water, score between 0.75 and 1. As a direct interaction, interactive farmers select their cropping pattern by imitating the decision-making approach of the majority of their neighbors; they mimic the decision criteria of the behavioral group with the largest number of neighboring farmers. The indirect interaction is simulated by considering a parameter like groundwater condition. In other words, by exploiting groundwater resources, each agent changes the groundwater condition as a common resource. In this structure, there is no coordination network.

10. Collectives

According to the behavioral group of farmers in this study, a number of farmers mimic the decisions of their neighbors. Therefore, not only are these farmers influenced by their neighbors, but also other farmers from different groups can act as role models for their neighbors and affect their behavior. On a larger scale, the behavior of the aggregate agents is evaluated while each farmer calculates the welfare level and considers the average profit in the study area. Therefore, the model's emerged result can affect each agent's behavior. This procedure has been introduced to the model by the modeler and is one of the assumptions of this work.

11. Heterogeneity

The number of agents simulated in this model is 1724. All the features assigned to them, including psychological and individual parameters, cropping pattern, cultivated area, and groundwater table, are considered heterogeneously. All these parameters form farmers' intention toward water conservation, which varies from agent to agent. Therefore, each agent differs from others in terms of the criteria based on which they decide. At the decision-making stage, these farmers act heterogeneously by calculating each farmer's willingness to conserve water resources; farmers are classified into four behavioral groups, each with different decision-making priorities. Farmers with a willingness score between 0 and 0.25 are categorized as active farmers, having the slightest inclination towards water conservation. Interactive farmers have a willingness score ranging from 0.25 to 0.5. Farmers fall into the semi-perceptive category if their willingness score is between 0.5 and 0.75. Finally, perceptive farmers, who are most willing to conserve agricultural water, score between 0.75 and 1.

In selecting the cropping pattern for the upcoming agricultural year, active farmers compare the estimated profit from three proposed low-water-demand crops: wheat, barley, and forage corn. They choose the cropping pattern that offers the highest profit as their next year's cropping pattern. Interactive farmers select their cropping pattern by imitating the decision-making approach of the majority of their neighbors; they mimic the decision criteria of the behavioral group with the largest number of neighboring farmers. Semi-perceptive farmers base their decision-making on balancing the water required for the chosen crop and the expected profit from the cropping pattern. While considering economic criteria, this group of farmers attempts to control their water consumption to avoid further deteriorating their groundwater status based on environmental criteria. Semi-perceptive farmers choose the crop that maximizes the parameter. The last group, perceptive farmers, select the cropping pattern for the upcoming agricultural year by choosing the crop with the lowest gross water requirement.

12. Stochasticity

To incorporate the stochasticity of complex systems, two parameters, including trust in authorities and livelihood dependence on agriculture, are considered to be set based on a random function. These parameters form the willingness of farmers to conserve water and change crop patterns. As these parameters affect the components that shape human behavior, they facilitate the incorporation of uncertainty into human decision-making.

13. Observation

The calibration of the agent-based model was fulfilled by comparing the value of the cultivation area of six major crops in the case study. Therefore, when the model runs for the whole simulation period, and farmers decide what crops they are willing to cultivate, the sum of cultivation area for the whole farmers is calculated and compared with the observed values of this parameter in this aquifer. Results at the agent level indicate that welfare status can play a more significant role in altering farmers' consumption patterns, where inadequate welfare may drive farmers towards profit-seeking behaviors, ignoring the critical condition of the aquifer and committing violations within the region. The willingness to conserve water varies among farmers across time and space according to their location characteristics and hydrological parameters. Therefore, the outcomes vary in a complex and stochastic manner. The results reveal that not only farmers' decisions can change groundwater conditions, but also groundwater levels can change farmers' decisions regarding whether they can cultivate low-water-consuming or high-water-consuming crops. The link between the past decision of farmers and their proceeding decision-making is perfectly reflected in this framework when farmers with wise decisions can earn more profit from agriculture compared to their neighbors with the same conditions.

Implementing the model in the Isfahan-Borkhar aquifer located in central Iran reveals significant impacts of two key parameters (i.e., aquifer conditions and welfare levels) compared to other identified parameters in farmers' consumption behaviors and the adoption of water-saving strategies. Moreover, results at the agent level indicate that welfare status can play a more significant role in altering farmers' consumption patterns, where inadequate welfare may drive farmers towards profit-seeking behaviors, ignoring the critical condition of the aquifer and committing violations within the region.

14. Implementation Details

This model runs using several buttons located on the NetLogo interface. There are multiple buttons on the interface through which different procedures are executed. The procedure for each button is briefly explained. The latest version of the model is uploaded as a private model for free download at the CoMSES Net at {Cross Ref}

15. Initialisation

At the time t = 0 of a simulation run, several parameters, including the psychological components of TPB and initial cropping pattern, are assigned based on the historical data from the database and the result of questionnaires. Historical groundwater depth is transferred from the hydrological model, which has been calibrated and initialized for five years of simulation before the start time of the agent-based model. As mentioned before, the initial parameters of this framework are imported from databases and do not change over time.

16. Input Data

The input data for this model includes a case study map, historical cropping pattern, historical pumping rates for orchard farming, industries and services, and domestic use, which remain constant throughout the modeling run and are incorporated based on a database received from a regional water company. Other constant inputs, such as age, education, agricultural experiences, dependency on agriculture, trust in authorities, and understanding of the consequences of land subsidence, have been considered based on the results of questionnaires. The constantly changing groundwater and welfare levels were calculated from a hydrological model and basic economic equations. The data used in this article are categorized into three main groups: hydrological information and parameters, economic data, and social and individual parameters for the Isfahan-Borkhar region. The hydrological information used in the MODFLOW groundwater simulation model includes bedrock information, hydraulic conductivity coefficients, specific yield, topography, rainfall, and infiltration, which were collected from the Water Regional Organization's database. The economic data used to calculate the profit and income for each farmer, which is one of the factors influencing decision-making, were collected from the Ministry of Agriculture Jihad in Iran.

Finally, the last series of data required in this article pertains to the social model of the study area. Initially, the factors influencing farmers' decision-making processes in the theory of planned behavior were identified based on interviews, questionnaires, and existing information in social reports. In this study, the number of simulated agents, including agricultural farmers, is 1724, and the behavior of other agents, such as orchard farming, industries, services, and domestic use, has been disregarded. Therefore, the groundwater extraction values for these agents are extracted from historical data and existing databases, assuming that all water needs of these agents are met. Based on existing social studies, previous research data, and conducted questionnaires and interviews, the influencing components on the characteristic of willingness to save water in agriculture are categorized into three main groups: psychological-social, economic, and environmental components.

17. Sub-models

We independently developed a distributed hydrological model to simulate groundwater levels and hydrological processes in an unconfined aquifer. This model was then tightly integrated into the agent-based model to comprehensively reflect the reciprocal feedback of these two models in a complex system.

In this study, the hydrological subsystem is simulated using a distributed model within the MODFLOW package, utilizing the GMS Software. MODFLOW software incorporates Darcy's Law and the law of mass balance to form the governing equation for groundwater flow in a porous medium, which ultimately takes the form of a Laplace equation (Equation 1).

In this equation, K_{xx} , K_{yy} and K_{zz} represent the hydraulic conductivity coefficients (L/T) in the x, y, z directions, h is the hydraulic head (L), W (volumetric flux per unit volume) indicates the sources and sinks (T^{-1}), t is time (T), and S_y is the specific yield (L^{-1}).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W = S_y\frac{\partial h}{\partial t} \quad (1)$$

The method for solving this equation in MODFLOW is the finite difference method. Despite the limitations noted in previous studies regarding the coupling of the MODFLOW model with agent-based models, the diverse hydrological packages of MODFLOW and its ability to simulate quantitative, qualitative, and land subsidence factors which themselves can be considered influential in future studies of farmers' behavior making this software a suitable choice for high-fidelity groundwater simulation. This justifies the complexity and computational costs of developing a socio-groundwater model.