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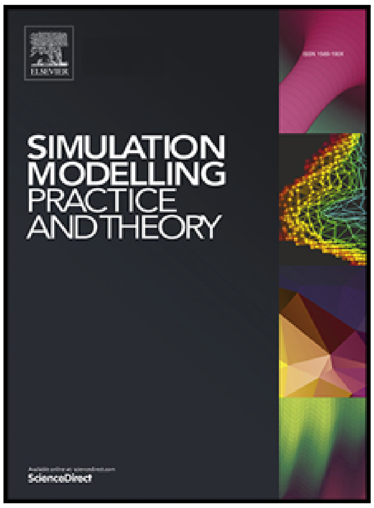

Using the Agent-based Model to Simulate and Evaluate the Interaction Effects of Agent Behaviors on Groundwater Resources, A Case Study of a Sub-basin in the Zayandehroud River Basin

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Using the Agent-based Model to Simulate and Evaluate the Interaction Effects of Agent Behaviors on Groundwater Resources, A Case Study of a Sub-basin in the Zayandehroud River Basin

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Abstract

The present study aims to identify and assess the parameters affecting agent behaviors and to simulate their effects on groundwater resources under the existing water regulations and policies. For this purpose, agent-based models are exploited to simulate the different groups of agents including Regional Water Authority, Public Prosecutor's Office, and the stakeholders as well as their interactions. The systems dynamic model is employed to investigate the effects of changes in agent behaviors on groundwater resources. The Any Logic software package is also used as a powerful tool for simulating both models and identifying the relationships between human behavior and water resources. Two efficient and inefficient scenarios are defined for assessing the effects of such parameters as 'meetings of regional water agencies held with other public organizations". Results revealed that changes in the behavior and interactions of Regional Water Authority with other public organizations under the first (inefficient) scenario led to increased renewable storage by 11.6 MCM while elimination of this parameter in the second (efficient) scenario led to a decrease of 52.6 MCM in renewable storage. Results of both scenarios showed that proper interactions of the Regional Water Authority with other stakeholders led to the control of illegal water abstractions and the rise of water table in the aquifers from the scenario

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one 1777.4 m to 1778.1 m under the second scenario.

Keywords: *Agent-based modeling, Any Logic, Interaction, Behavioral rules, Systems dynamic*

1. Introduction

The changing conditions as realized by population growth, increasing water demand, declining water resources, and climate change have led to an increasingly complex system of water resources management. It is essential for the human society to identify these changes, determine their impacts, and estimate their extents in order to define measures to control some and to adapt the society to others. It is the main objective of water resources management to strike a balance between supply and demand and to adapt the human society to the prevalent conditions aimed at sustainability in water resources and the affected systems.

An important issue in water resources management is to use the resources so as to meet a variety of demands. It is these varied demands and the many water-related political, social, ecological, and economic issues that complicate the management of water resources because of the differences and conflicts that arise in exploiting water resources. In situations where more than one body (group or organization) are involved, differences arise due to their goals, viewpoints, and priorities, which make it obviously difficult for decision-makers to reach unanimity and common grounds for adopting policies [24].

The major decision-making bodies in Iran have always made efforts to develop the best possible image of the prospects of the region under their rule (be it the state, a province, or a river basin) with the present conditions viewed as their launching pad, which naturally makes the exploitation of water resources more complex. At the macro-policy-making level, efforts have been directed toward economic growth as well as agricultural and industrial development to achieve food security while the users' relative satisfaction is also secured. Water resources management in Iran has thus been affected by major national plans so that water has been supplied, one way or another, to all development projects across the state. For instance, the Zayandehroud River basin, one of its sub-basins being Lenjanat covered in the present study, has continually witnessed agricultural and industrial development projects since 1950. Water deficit in the region has been responded to by constructing dam reservoirs, water tunnels, and different inter-basin water transfer projects. Indeed, whenever the basin or its stakeholders faced water shortage, short-term water supply plans were executed. Clearly then, water managers in the region always opted for short-term management plans of supplying water as compensation for shortages rather than subscribing to demand management as an example of long-term and sustainable plans aimed at enhanced water productivity. Fig. 1 depicts the rising trend in water demand and water development projects over the years. This type of decision never allowed the stakeholders to appreciate the water deficit problems in these years such that, even during drought periods with serious water scarcity, their demands were properly met by imposing exorbitant pressures on groundwater resources.

Also, the considerable increase in the number of stakeholders because of consecutive development and water users in the absence of any thought-out plans has caused an imbalance between the water management organizational capacities and the number of water users involved [23].

Fig 1. Development of ZayandehRood river basin water resources and water consumption [Tavakoli]

Fig. 2 gives an image of the decision-making structure in the different levels across the nation. The topmost (i.e., the third) level represents the major decision-makers at the macro-political level. Based on their predefined responsibilities, their efforts are typically directed at making proper decisions for various areas of activity; these decisions are normally formulated within the framework of general and comprehensive plans expected to achieve development goals. The most important of these goals often include economic development, increased industrial production, food security, and self-sufficiency. Although the topmost decision-making level subsumes a wide variety of sectors that make decisions in and for varied fields, it must be noted that these sectors are basically interrelated and can, therefore, assist each other synergistically toward achieving their general development and sustainability goals.

But decisions at the macro level are often adopted without due consideration for the principles of water demand management. The lack of coordination at the management level is basically due to the understandable desire for economic development over short periods. in such a way that all the stakeholders become satisfied, which evidently encourages non-expert and biased decisions (without due regard to the requirements by the bodies and institutions involved) as attempts to meet the contradictory goals of different stakeholders [23]. Based on the above considerations, it follows that the national development goals do not receive identical weights. For example, despite the reliance of most items in the Sixth National Development Plan on water resources in Iran, only a few have laid emphasis on the importance of water resources management [13].

Differences in weights assigned to different goals are reflected in the importance attached to certain policies and plans when being executed by the second level management. Water resources conservation policies, in this regard, are not much cared for at this level despite the fact that an integrated approach to water resources management involves equal consideration paid to economic, environmental, technical, and social issues while maximum efforts are simultaneously devoted to the conservation of water resources for the generations to come (Ebrahimi et al., 2015). Interestingly, but unfortunately, the feedback from the second management level causes that the stakeholders (level one) focused their attention solely on maximal exploitation of the resources.

The structure of water resources management in Iran is depicted in Fig. 2. In this structure, the topmost, or third level, comprises the Ministry of Energy (in charge of water resources development), the second level includes all the Regional Water Authorities, and the stakeholders collectively constitute the first level. The third management level is in charge of adopting policies and passing laws and regulations in response to current conditions and demands. Almost all the policies and laws adopted up until now are highly adequate and of good quality; these laws have also been supplemented through time when necessary. The second management level is mandated to implement and execute the policies and laws promulgated by the topmost management level. This is clearly an important responsibility of great impact, especially as this management level is also in charge of disseminating the laws and regulations among other agencies involved and the stakeholders as well. However, the greater concerns shown by this management level (all of the agencies except Regional Water Authorities) for food security and economic development have obstructed the successful achievement of its goals.

One drawback, however, of the present water management system in Iran is the nonexistence of deterrent measures to enable regional water authorities to prevent and/or intercept breaches of law. While these companies have at their disposal measures to issue permits for water use and abstraction by stakeholders, they have no legal permission to deter violations of law. Even worse, they lack any legal power to cancel, desist, or suspend previously issued permits. Instead, violations of law can only be sued through a long court procedure. This is while government agencies usually avert any strict and stringent law enforcement measures taken by regional water authorities merely to avoid social tensions at the local level (i.e., the first management level) and to win stakeholders' satisfaction and support. Thus, the views held by the top level management and the nonexistence of deterrent measures in the hands of regional water authorities have led to impoverished guarantees for the conservation of water resources and to the failure to properly enforce the laws. It is the predominance of this mindset over the years that has strengthened the stakeholders' resistance against policies and laws to the extent that not only has the enforcement of even the most primitive and basic laws but also the control and surveillance of illegal water abstraction become formidable and impossible in some regions.

Fig. 2. Structure of decision making for different levels in Iran

This non-coordinated management system combined with water extraction beyond the natural potentials of the region has gradually led to development beyond a region's capacities. The trend has inculcated in local stakeholders the idea that it is possible to maintain incessant development. This is while the demand management strategy has led to oppositions by the stakeholders [16]. The combinations of these conflicts and expectations along with the measures taken by the decision-makers and executive bodies have led to the declining efficiency of the presently existing regulations and control policies. From a different perspective, the problems associated with water resources management in Iran reveal poor cooperation and trust among the different stakeholders as a result of poor social assets. Indeed, water governance is facing serious problems as a result of lack of integration and unison among the parties involved [26].

Accordingly, the failure of the first and second management levels may be claimed to form the major problem in water resources management, in this present study aims to simulate the behavior of the different agents (i.e., regional water authorities, the Public Prosecutor's Office, and water stakeholders) to model and assess the effects of these agents. Moreover, a hydrological simulation is accomplished of the effects of changes in the behaviors of the agents on groundwater resources. In this process, the above two simulation models are observed to be in close relationship at each time step such that changes in agents' behavior are witnessed to steadily affect the water resources.

These two levels were simulated in the present study and the agent-based model was used to represent the water resources management, to determine the weights of the interrelationships and interactions among the decision-makers at the first and second levels in executing laws and regulations, and to investigate the mutual impacts of the agents and changes in their behavior within the framework of different scenarios.

The agent-based model is a newly developed tool recently used on a wide scale for the simulation and evaluation of such complex systems as water resources [6]. These models are employed as a tool for the simulation of human social life and the reciprocating interactions of different players [22].

Agent-based models serve as tools for simulating different groups [27]. The players in such models are seen as independent institutions or units that cooperate and work together in a common environment [25]. Each player is identified as an agent that is a unit in the whole and that is capable of establishing relations with both other agents and the surrounding environment. The models draw upon the way different groups affect others or are affected by them to simulate and represent the human decision-making process [2].

The objective in the studies using the agent-based models is to simulate real-life conditions as defined by regulations. In this process, the prevalent conditions are surveyed and data are collected to formulate behavioral rules that are then used in simulating the agents. Below is a brief literature review of studies using agent-based models.

Becu et al. [7] used the agent-based model for simulating the behavior of farmers. In their study, each farmer's capital and labor were identified as his main characteristics. At each time step, the farmer would make decisions about his desired crop pattern based on his capital, labor, and available water. Berger et al. [8] developed a model to explore the complexities of water resources systems. In their model, the agents cooperated toward improving their water conveyance system. Additionally, the model allowed the agents to trade their water and property and to share information on modern irrigation systems. Employing an agent-based model, Van Oel at al. [29] classified farmers into the three categories of those using river water, those using flood water, and those dependent on storage dam water. Each category of farmers in this model would have their own estimates of the adequate amounts of water and precipitation on which they would base their cropping decisions.

Akhbari and Grigg [3] modeled the Sacramento-San Joaquin basins and determined the agents involved and their characteristics. Their model consisted of the three components of a basin model, an optimization model, and an agent behavior simulation. The optimization-simulation model was meant to determine the interactions among the objective functions while the behavior simulation was meant to capture agents' interactions and reactions toward water allocation decisions. In this study, questionnaires were used for data collection. Results showed that a compensation of 21% for the expenses incurred on the agents due to cooperation led to a reduction of 30% in water consumption, an increase of 22% in river flow, and a reduction of 12.5% in salinity. It was also revealed that social pressures in the absence of compensatory incentive programs might lead to reductions of only 4.5% and 4% in water consumption and salinity, respectively. Farhadi et al. [12] investigated the changes in farmers' water demand and agent behavior in Fars Province, Iran. They used the combined basin simulation, optimization, and agent-based simulation model. Results indicated that interactions with the farmers and formulation of penalties led to reduced water demand and improved aquifer status. In a recent study, Darbandsari et al. [11] investigated the effects of water pricing, awareness raising, income level, and hydrological conditions on the behavior of domestic water users in the western part of metropolitan Tehran. They found that a raise of 30% in water prices would yield the best scenario for water consumption management under all climate conditions if awareness raising were high and public income were only about normal rates.

Giuliani et al [15] employed human agents to investigate cooperation within the agriculture sector under climate change. In their human-nature model under the effects of likely climate change in the future, the authors simulated the effects of management policies to show that dynamic coordination of water supply and demand under this policy led to a decline in water wastage in Ada basin worth 10 million Euros while a one-way coordination was found to be of no considerable impact. Cai and Xiong [10] used an agent-based simulation of cooperation in irrigation demand to investigate the effects of using initial participant and government support on the rate and level of achievements due to local cooperation. The model was based on the authors' conception of the basic mechanisms commonly employed by rural households. Their results revealed that while government support played the major role in promoting cooperation among farmers, the primary players and the network structure were of no great impact. Anthony and Birendra [5] used the agent-based model to evaluate irrigation management strategies. They proposed an agent-based model for prioritizing irrigation allocations according to such parameters as crop sensitivity to drought, growth stage, soil type, and crop production rate. Results indicated that their proposed agent-based model was able to achieve a great saving on irrigation without jeopardizing production. In their combined study, Furqan Khan et al. [21]

employed the SWAT semi-distributional model and a non-centralized water supply system within an agent-based model to investigate the effects of different water resources management strategies. The method developed in this study was mainly aimed at improving stakeholder appraisal of a complex system and their understanding of different methods of developing water basin management systems. In this model, the agents made annual decisions on water allocations to agriculture, hydropower generation, and environment while they updated their decisions each year based on the experience gained from the preceding year.

Some previous studies have been based on regulations and policies that took a top-bottom view with no bottom-up feedback. In other words, the regulations were inflexibly enforced so that the stakeholders were solely considered as the ultimate executors of laws. This is, however, in sharp contrast to the reality as stakeholders typically violate these regulations.

The studies using agent-based models generally pursued a variety of objectives such as exploring the likely relations between hydrological and social issues, investigating the effects of stakeholder decisions on management strategies (changing crop pattern, water pricing scenarios, compensatory expenses), detecting relationships between the different groups, combination of hydrologic model and decision human model and feedback of water users' behavior. Previous studies have exploited different components of the agent-based models depending on their objectives.

The main goal of the present study is to simulate the real-life behavior of first and second level agents and their interactions. These interactions and interrelationships are expected to affect the agents' behavior and the feedback to influence the conditions of groundwater resources. The simulation model is developed based on real conditions to determine the effects of changes in agent behavior on controlling violations, conserving resources, and changing groundwater levels. The relationships and interactions among different agents are modeled using real-life data (through a survey of the existing water wells and the related lawsuits) given the fact that the process in filing a lawsuit, indeed, reflects actual agent behaviors.

More specifically, the agents involved and their behaviors are characterized by investigating the characteristics of both the local stakeholders and the officers at the Regional Water Authority at Lenjanat sub-basin of the Zayandehroud Basin. In a second stage of the study, the interactions are simulated based on the regulations and policies enforced in the region and the results of these interactions are determined by establishing behavioral and hydrological models over the whole simulation period under two different scenarios. It is the aim of the present study to evaluate the enforcement of current regulations and policies. Using a specific region, the study is expected to disclose the effects of changes in the behavior of Regional Water Authority as one agent and their interactions with other agents on the enforcement of laws and regulations and their control powers over illegal water withdrawal from the wells in the region. Finally, the parameters affecting these interactions and water abstraction controls are identified and their effects determined while the feasibility of executing one specific groundwater resources management policy is also assessed.

2. Methodology

In pursuit of the objectives outlined above, the present study was conducted in three stages Fig. 3. The first stage involved the development of a comprehensive database for which data were collected on the groundwater resources (wells and Qanats) in the study region, quantities of water withdrawals, hydrological information (including precipitation, evaporation, groundwater inflows and outflows, recharge from surface flow and rainfall, and return flows from water consumed in different activities), number of authorized wells and the approximate number of illegal wells, agents and their behavioral characteristics, and relevant data from the lawsuits filed on illegal wells in the study region. Also, in this step, field investigations were performed to differentiate between authorized from illegal wells and to estimate the abstractions from groundwater resources in the region, to determine the time spent on court processes for a breach of law (derived from the survey of example lawsuits), and to identify the agents involved.

Hydrological data were extracted from the reports available at Isfahan Regional Water Authority while the data on stakeholder violations and the court processes were extracted both from the lawsuits available at Isfahan Regional Water Authority and through interviews with experts.

The second stage involved the development of a conceptual agent-based model in three sections: 1) identification of the main challenges, agents, behaviors, regulations, and policies; 2) identification of agents and description of their states; and 3) implementation of the agent-based model thus formed in the software environment. Once the main challenges in the management of water resources in the region were identified, the agents involved, their behaviors, and the main regulatory and policy problems were explored and identified. In this process, it was important to identify the agents which caused the failure to control withdrawals from illegal wells. These agents included such regulations as "the executive order for clarifying the status and operation of illegal water wells" as well as public organizations and their behavior with direct impacts on water resources management. Organizational agents involved in law enforcement included regional water authorities and public prosecutor's office.

The agent-based model was developed based on the agents identified and their states, functions, and interactions in response to real-life requirements and conditions. Finally, the model thus obtained was simulated in the software environment. Considering the existing conditions and the agents' past behavior, the model simulated the measures and instruments used to control breaches of law.

Implementation of the water resources simulation model formed the third stage. Initially, system boundaries were defined and the different components of the water resources system were developed before the relevant data were inputted into the model. This was followed by calibration and verification of the model to prepare it for the simulation stage based on the research assumptions, regional conditions, and agent behaviors.

The fourth stage involved the development of different scenarios and evaluation of their impacts on water resources. For the purposes of this study, the two efficient and inefficient scenarios were defined in which the effects of changes in the behavior of the regional water authority and its interactions with other public organizations on improving groundwater resources were evaluated. Finally, the possibility for achieving the short-term objectives of one of the management policies adopted at the predefined time horizon was explored.

Fig. 3. Research stages

2.1. Agent-based model and theory governing agents' behavior

In agent-based model, an agent is defined as an individual, group, stakeholder, institution, or organization that possesses and exercises decision-making powers. Indeed, an agent may be viewed as a player with unique characteristics and powers that it uses in making decisions. Agent characteristics include independence, memory, experience, expertise knowledge, updatability, and ability to interact with others. Each of these can be modeled depending on the requirements in each case. While some researchers define each agent as one component of the system, others maintain that an agent is characterized by its updatability and adaptability [20]. Interactions occur as a result of relations between two agents during which messages might be communicated with impacts on the behavior of each agent involved. Put differently, interaction is the result of relations among agents and the success and affectability during these relations depend on the specific characteristics of each agent. Obviously, no reciprocal changes can be expected in agents if no relations exist and when no interactions occur in the system [9]. Generally speaking, an agent's understanding of the environment is a reflection of the feedback it receives from that environment and its components. Development of agent-based models relies on the identification of agents and their behaviors, definition of the environment in which the agents interact with each other, and formulation of the rules according to which the agents interact with each other and with their surrounding environment [9]. The effects of relations on an agent are then determined based on the rules promoting a new behavior by the agent after it interacts with others in the system. Moreover, these effects are strongly influenced by environmental conditions and agent interactions [9].

A number of methods, including the if-then rule, threshold points (min and max values), and objective function method, are available for extracting the rules governing the behavior of different agents. Depending on the objectives of each special study, however, the microeconomic, psychological, cognitive, experience-based decision-making, statistical, empirical, or evolutionary programming models may also be used for this purpose [4]. Moreover, empirical data reflecting real-life behavior can be exploited to model agent behavior [18]. In the present study, behavioral rules were extracted from empirical data since real-life data (an archive of lawsuits filed) were available in which each lawsuit on each illegal water well reflected the behaviors of the different agents involved. Thus, behavioral rules were extracted from empirical data for which observational and experiential data obtained from the lawsuits were used.

2.2. Analyze of water resources management system and its Components

Water resources and their users are the indispensable and inseparable components of a water resources system. The regional water authority is the monitoring body in charge of not only the protection and proper operation of resources but also the control of water withdrawals. Breaches of regulations are left to the hands of the public prosecutors to deal with. Thus, water resources, regional water authority, and the public prosecutor's office are considered as the main components of the system investigated in this study. In this system, standing relations exist among the agents (stakeholders, regional water authority, and public prosecutor's office) and the water resources (i.e., the environmental agent). While the users are constantly abstracting water from the resources, the regional water authority is constantly monitoring consumption rates and the water balance. This keeps these two agents in constant interaction with the environment while they are additionally interacting with each other. Typically, these relations and interactions become more pronounced when problems arise in the water resources or at times defects occur in the water works used by the stakeholders. In cases when a stakeholder violates the laws and regulations, the public prosecutor also enters the scene. Unauthorized well drilling and water abstraction are examples of the violations that are widely committed across the nation and that adversely affect groundwater resources. A great portion of the time and resources of the national water resources management bodies are devoted to controlling these violations through enforcing the policies and regulations. All these have been, therefore, included in the simulations in this study.

2.2.1. Water regulations and policies (well drilling and resource exploitation authorized by the

Ministry of Energy)

Water resources in Iran are governed by a total number of 13 laws, 20 codes, and 4 directives. The most important law is that of "Fair Water Distribution Act" adopted in 1983. The second chapter of this Law deals specifically with groundwater resources. The importance of groundwater resources in Iran and the heavy reliance of users on these resources have led to the adoption and promulgation of relevant codes and directives on the use of groundwater resources. The "Executive Code on the Second Chapter of Fair Water Distribution Act" of 1985 provides detailed directions for the enforcement of the Fair Water Distribution Act as pertains to groundwater resources.

Unauthorized water well drilling and illegal water withdrawal are common in most parts of Iran. A vast number of such illegal wells are in operation across Iran. The existence of these wells led to the promulgation in 2010 of the executive order for "clarifying the status and operation of unauthorized water wells". A most recent policy adopted in 2015 by the Ministry of Energy is the "Groundwater Resources Reclamation and Balance Scheme" that comprises 8 directives. Each directive pursues a certain goal, the most important being the third directive that aims at controlling, decommissioning, and plugging all illegal wells to restore the water balance in aquifers. As it is the objective of this study to address the control of illegal wells, some of the regulatory provisions that prohibit unauthorized well drilling as an attempt to sustain groundwater resources will be reviewed below.

1.Fair Water Distribution Act: Item 3 of this Act states that groundwater extraction through wells can only be accomplished under licenses and with prior authorization by the Ministry of Energy. Item 45 describes the cases in breach of this Act and the related penalties [17].

2.Executive Directive on Chapter 2 of the Fair Water Distribution Act: Item 24 of this Directive describes the measures to be taken by and the instruments available to the officers of regional water authorities in cases when individuals violate the laws and regulations. Paragraph 2 of Item 24 mandates that illegally drilled wells should be sealed and plugged and the unauthorized installations removed by the owner within 20 days of receipt of a written notice. In case the owner fails to comply, the officers of the regional water authority are allowed to take immediate direct actions. Their actions must be preceded by a minute of the meeting prepared and signed by the officers stating the violation of the Fair Water Distribution Act committed by the owner. The report on such violations must be also communicated to the local public prosecutor's office to sue the violator. The final legal processes must be completed by the lawyers and legal advisors of the regional water authority [1].

3.The third Directive involves the simultaneous enforcement of the Optimal Use of Agricultural Water Act and the "executive order for clarifying the status and operation of unauthorized water wells": The main objective in this case is to restore the water balance in the aquifers across the state over a period of five years. This requires the decommissioning and plugging of all illegal wells while the discharge from authorized wells is also reduced in proportion to the aquifer water table such that the water balance shifts from the present negative value to zero.

2.2.2. Agents

Based on field investigations, the three agents of direct impact on the modeling procedure were identified to be stakeholders, regional water authority, and the public prosecutor's office. The water resources system is recognized as the fourth agent, which is itself affected by the behavior of the first three.

- **Stakeholders (St)**

This group includes the agents who use water to generate an economic value. Farmers are included in this category as they need water for improved farm productivity. Whatever the prevalent conditions or the agent's characteristics, the agent's goal is enhanced productivity of water resources. Thus, this agent not only is in constant contact and relations with the regional water authority but is also affected by it. In breaches of law by this agent and their insistence on continued violation of the regulations, the stakeholder will come into contact with the public prosecutor's office as well. For the purposes of this study, examples of farmer stakeholders were reviewed who faced indictments of unauthorized well drilling and water abstraction.

- **Regional water authorities (RWA)**

This agent group is not only responsible for supplying water to stakeholders but is also in charge of surveillance and control of water withdrawals by the stakeholders in compliance with prevalent regulations and to prevent their violation of the laws. Thus, in addition to meeting the stakeholders' water demands, this group is mandated to preserve and protect water resources and to maintain the balance between available water resources and withdrawals. This keeps this agent in constant relationship with the stakeholders. Regional water authorities are mandated to communicate written notices to those stakeholders who break the law. Failure on the part of the stakeholders to take proper actions will lead to the preparation of a violation report and a lawsuit filed by the regional water authority to the public prosecutor's office in compliance with the relevant regulations.

- **Public prosecutor's office (PPO)**

The public prosecutor's office will come into play as an agent in cases where the law is violated and when a lawsuit is filed and submitted by the regional water authority. The decisions and verdicts by the public prosecutor's office are deemed binding for both the regional water authority and the stakeholder. However, it might happen that the decisions announced by this agent are suspended under certain conditions.

- **Water resources system**

All the users, policy makers, and decision-makers as an agent group affect the water resources system directly or indirectly. The system is not only affected by changes in the behavior of other agents but also by environmental factors such as climate conditions. It is, indeed, the combination of behaviors as well as policies and regulations adopted by the human agent and such climatic parameters as precipitation, evaporation, and infiltration that affect the discharge and recharge rates of a water resources system [30]. In the present study, the water resources system is initially modeled as an affected system using a systems dynamic model.

2.2.3. Creating rules governing agents' behavior in the framework of agent-based model

A number of methods, including the if-then rule, threshold points (min and max values), and objective function method, are available for extracting the rules governing the behavior of different agents. Depending on the objectives of each special study, however, the microeconomic, psychological, cognitive, experience-based decision-making, statistical, empirical, or evolutionary programming models may also be used for this purpose [4]. Moreover, empirical data reflecting real-life behavior can be exploited to model agent behavior [15]. In the present study, behavioral rules were extracted from empirical data since real-life data (an archive of lawsuits filed) were available in which each lawsuit on each illegal water well reflected the behaviors of the different agents involved. Thus, behavioral rules were extracted from empirical data for which observational and experiential data obtained from the lawsuits were used. The rules thus extracted are introduced in the following section and the relationships and the state of each agent together with related functions and codes are presented in Fig. 4.

The regional water authority, as an agent, acts within its own standards and policies but it is also affected by the behaviors of the stakeholders and other agents involved.

1. A notice is issued in writing at the detection of an instance of violation of law but no more action is taken until the legal due date is reached.
2. No reaction by the stakeholder to the notice triggers the process for filing a lawsuit for submission to the Public Prosecutor's Office to control the law violating act.
3. If the above process leads to no final verdict or sentence by the Public Prosecutor, the relevant evidence and documents are resubmitted.
4. At the issuance of a final verdict, the illegal well is plugged and decommissioned.
5. In case the court verdict or sentence cannot be executed, actions will be taken for a second round of controlling the act of fraud.
6. Communications and interactions are established with other public organizations to facilitate the process of controlling acts of fraud. Such interactions are introduced into the model as parameters.
7. Regional water authorities are directly affected by the public prosecutor's office but indirectly by stakeholders.
8. The durations for the different processes are based on real time processes.

The stakeholder agent reacts in accordance with local conditions and receives feedback from other agents. The reactions may be outlined as follows:

1. The stakeholder might show no reaction at the receipt of a notice and continue with their unauthorized water withdrawal.
2. They defy court decisions.
3. In some cases, they either provide detailed descriptions of their conditions as excuses or use men in power and influential people to postpone the execution of court decisions.
4. Stakeholders are directly affected by the laws and regulations of both the regional water authority and the public prosecutor's office.
5. In simulating the process, real times are included in modeling the processes (such as receiving notices and taking proper actions).

The public prosecutor's office is not activated unless they receive a complaint. The agent acts according to the following rules:

1. Reports of violation of law submitted by the regional water authority activate this agent.
2. They hold meetings with the other two agents involved to reach a conclusion for issuing a final verdict.
3. They directly affect the performance of the other two agents.
4. They are directly affected by the other two agents.

Fig. 4. Interactions among the agents and violation control procedure

It is now time to turn to a description of the modeling process and the functions used based on Fig 4. The relations and interactions depicted in this Figure are based on the objective of simulating the regional water authority's control of violations and frauds by the stakeholders. Clearly, each of the three agents of regional water authority, stakeholders, and public prosecutor's office uniquely perform according to their procedures and regulations but interact with the other two. In this Figure, the states and transitions of each agent are denoted by numbers and letters, respectively.

In the model developed in this study, the RWA (regional water authority) communicates a written notice (reaction of RWA) when a violation is committed by the stakeholder (stakeholder's action) and the stakeholder agent is mandated to halt the fraudulent action within the specified time.

$$\text{RWA Agent:}\left(\text{Transition a: Func1=}\{\text{Send message "}\textit{Should Be Filled}\text{" to all abusives}\}\right) \tag{1}$$

According to (1) above, the message *"Should Be Plugged"* is communicated to all violating stakeholders.

$$\text{St Agent:}\left(\text{Transition a: Func2=}\{\text{Receive message "}\textit{Should Be Filled}\text{" from RWA}\}\right) \tag{2}$$

Relation (2) above represents the receipt of RWA's notice by the stakeholder. Once these functions are accomplished, the regional water authority will be in State 1 and the stakeholder agent in State 2. RWA waits for a reaction by the stakeholder in the time running up to the due date, which is a period specified by RWA's regulations. Once the legal time is over, the stakeholder enters State 3 when he is expected to make a decision (Fig. 4), which may mean either no action, continued violation of law, or immediate cessation of water withdrawal. Based on the review of the existing lawsuits, the conditions observed in the region, and interviews with experts, all the stakeholders were found to opt typically for the second decision and continue with their unauthorized water abstraction, which means that the first part of Relation (3) is never activated during the simulation period. In other words, a written notice does not suffice to stop violation of law, by which the stakeholder enters State (4).

$$\text{St Agent:}\left(\text{State 3: Func3=}\left\{\begin{matrix}\text{Time out=}t_w\text{: if condition true:}\{\text{Block himself and go to state 5}\} \\ \text{else }\{\text{Do not block and go to state 4}\}\end{matrix}\right\}\right) \tag{3}$$

where, t_w denotes the legal time for the cessation of law violation by the stakeholder.

Based on the stakeholder's reaction, the RWA agent in State (1) receives the message of no cooperation, which instigates him to prepare a report for submission to the central office requesting for appropriate orders. The necessary steps are then taken within the organization to file a lawsuit for submission to the public prosecutor's office. The number of reports that can be prepared at RWA at each time step is limited due to the limited number of staff members. For the purposes of this study, minimum and maximum numbers of reports that could be potentially prepared at RWA were defined based on the available statistics and expert views. Functions (4-6) in Relation (4) represent the receipt of the "*No Plug*" message, transmission of the message "*Your time over*", and the number of reports submitted to the central office, respectively.

$$\text{RWA Agent:}\left(\text{State 1:}\left\{\begin{array}{c}\text{Func4=\{Receive message "}\textit{No Fill}\text{" from abusives\}}\\ \text{Func5=\{Send message "}\textit{Your time over}\text{" to all abusives\}}\\ \text{Func6=}\left\{\begin{array}{c}\text{for timeout=}\textit{Month():}\text{ Num.reports=}\textit{uniform\_discr}(R_{min}\ ,R_{max})\\ \text{and preparing violations reports and send to central office}\end{array}\right\}\end{array}\right\}\right) \quad (4)$$

where, *timeout* and *Num.reports* represent the modeling time step and the number of reports submitted to the central office, respectively. Uniform_discr(,) is a probabilistic uniform function that selects a random value between the min and max. Finally, R_{min} and R_{max} denote the minimum and maximum numbers of observational reports delivered at each time step, respectively.

At this stage, RWA as an agent enters State 2 waiting for orders from the central office. In the model used here, vectors are also defined which stores information on each agent in each state. For instance, a vector defined for this stage stores information on the number of reports confirmed. Thus, the value for this vector becomes positive immediately after the first report is confirmed when the agent RWA enters State 3.

$$\text{RWA Agent:}\left(\text{Transition C: Func7=}\begin{Bmatrix}\text{Timeout= month (): If } \mathit{Num.ConfirmedReports}\text{>0:} \\ \text{go to state 3 and send reports to co Agent}\end{Bmatrix}\right)$$

(5)

In this Relation, *Num.ConfirmedReports* represents the number of reports confirmed by the central office.

In the following stage, the public prosecutor's office receives the report and becomes activated.

$$\text{Co Agent:}(\text{State 1: Func8=}\{\text{Recieve message "}\mathit{Violation\ Reports}\text{" from RWA Agent}\}) \qquad (6)$$

In Relation (6), the message *"Violation Reports"* is delivered by the RWA to the public prosecutor's office. The public prosecutor then holds meetings to review the documents and reports in a rather time-consuming process. The total time spent on a case from the examination of the data to the time a verdict is issued ranges from a minimum to a maximum (Et_{min}, Et_{max}) for a limited number of reports (CR_{min}, CR_{max}). In the present model, the process time and the number of reports attended are stochastically selected from values ranging between minimum and maximum observed values using a uniform probabilistic function.

$$\text{Co Agent:}\left(\text{State 2: Func9=}\begin{Bmatrix}\text{For EvaT=}\mathit{uniform\_Discr}(Et_{min}, Et_{max})\text{:} \\ \text{evaluate NER=}\mathit{uniform\_Discr}(CR_{min}, CR_{max})\end{Bmatrix}\right) \qquad (7)$$

where, Et_{min}, Et_{max}, CR_{min}, and CR_{max}, respectively, represent minimum and maximum observed process times for the review of a report and the minimum and maximum numbers of reports reviewed by the public prosecutor.

The process begins with an initial review before an in-depth final examination is conducted and ends with a final court verdict based on the content of the report. Examination of previous cases reveals that some lawsuits receive a positive verdict (γ) while others have negative ones ($100-\gamma$).

$$IS=\frac{NER}{EvalT} \tag{8}$$

where, IS denotes the total number of verdicts in a given time step expressed as the ratio of reports evaluated over the study period. The number of positive and negative verdicts might be calculated using the following relations:

$$PIS=\gamma\times IS \tag{9}$$

where, PIS denotes the number of positive verdicts issued and γ is the percentage of the total positive verdicts.

$$NIS=IS\text{-}PIS \tag{10}$$

where, NIS is the number of negative verdicts.

Vectors are also defined at this stage in which the characteristics of the stakeholders processed (equal to IS) are stored from which the PIS value for positive verdicts and the NIS value for negative verdicts are stochastically selected.

$$\text{Co Agent:}\left(\text{State 3: Func10}=\left\{\begin{array}{c}\text{For timeout=month():}\\ \text{make collection with size } \mathit{IS}, \mathit{PIS} \text{ and } \mathit{NIS};\\ \text{Select random from } \mathit{IS} \text{ with size } \mathit{PIS} \text{ and}\\ \text{Issue positive sentences}\\ \text{Issue negative sentences for remaining;}\end{array}\right\}\right) \tag{11}$$

where, PIS, NIS, and IS represent the magnitudes of the vectors constructed in the model.

Once a verdict is issued, both RWA and the stakeholder are notified of the result at which stage the stakeholder enters State 6 and RWA enters State 4 upon receipt of the message.

$$\text{Co Agent:}(\text{State 3: Func11}=\{\text{Send message "}\textit{Sentences is ready}\text{" to RWA and St Agent}\}) \tag{12}$$

In this Relation, the message “*Sentence is ready*” is forwarded to both RWA and the stakeholder.

Once the number of verdicts issued becomes larger than zero, RWA enters State 4, indicating that they should consider plugging the illegal well.

$$\text{RWA Agent:}\left(\text{Transition d: Func12=}\begin{Bmatrix}\text{If } \textit{Num.issuedSentences}\text{>0:} \\ \text{go to state 4}\end{Bmatrix}\right) \tag{13}$$

Relation (14) shows the receipt of the message by the stakeholder.

$$\text{St Agent:}(\text{Transition e: Func13=Recieve "Issued Sentences"}) \tag{14}$$

If the verdict is a positive one, RWA goes about making provisions for its execution. If negative, RWA embarks on collecting new evidence and preparing fresh documents. In the last stage, RWA makes the necessary provisions for executing the court decision. Experience and review of previous cases reveal that it may not be possible to decommission and plug the well in some cases due to the special conditions prevailing and the tensions created.

$$\text{FN}=\beta\times\text{PIS} \tag{15}$$

In which, FN represents the number of wells plugged and β is the RWA's success factor which depends on its experience and interaction with the stakeholder.

$$\text{NFN}=\text{PIS}-\beta\times\text{PIS} \tag{16}$$

Relation (16) is used to calculate the number of illegal wells remaining unplugged.

$$\text{RWA Agent:}\left(\text{State 4: Func14=}\begin{Bmatrix}\text{For timeout=month():} \\ \text{Make collections with size FN and NFN} \\ \text{Select random from PIS collection with size FN} \\ \text{and go to state 7} \\ \text{go to state 5 for remaining}\end{Bmatrix}\right) \tag{17}$$

If the number of illegal wells remaining unplugged is larger than zero in RWA's performance diagram, this agent is moved from State (5) to (6) and once new documents and evidence are collected, it is returned to State (3) for the re-examination of the documents. Similarly, if an illegal well remains unplugged in the stakeholder's performance diagram, the stakeholder is moved from State (7) back to State (4).

2.2.4. Rules governing the water resources system hydrology

The parameters and factors affecting the recharge and discharge of groundwater resources include groundwater inflows; rainfall infiltration rate; surface infiltration rate; groundwater recharge from agricultural, industrial, and domestic return flows; drainage; evaporation from aquifers; and groundwater outflows. The general groundwater balance equation may be written as follows:

$$\Delta V = I_G - \alpha \times P + \beta \times SW + RF_{Ag} \times Ag\_Ex + RF_{In} \times In\_Ex + RF_{Re} \times Re\_Ex - Q_G - Ag\_Ex - In\_Ex - Re\_Ex - Ev + FN \times Q_{illegal} \quad (18)$$

where, ΔV (m^3/month) represents fluctuations in volume of aquifer water; I_G (m^3/month), the underground inflow; P(m^3/month), precipitation in the region; α, rainfall infiltration rate; RF_{Ag} (m^3/month), agricultural return flow; Ag_Ex (m^3/month), agricultural water consumption (the sum of legal and illegal withdrawals); RF_{In} (m^3/month), industrial return flow; In_Ex (m^3/month), industrial water consumption; RF_{Re} (m^3/month), domestic return flow; Re_Ex (m^3/month), domestic water consumption; Q_G (m^3/month) groundwater outflow; Ev (m^3/month), evaporation from the aquifer; FN the number of wells plugged in one month; and $Q_{illegal}$ (m^3/month) is withdrawals of illegal well.

The fact that the model for the water resources system is linked to the agent-based model allows for the effects of agents' behavior at each time step on water abstraction to be duly reflected in fluctuations in water table.

The Any Logic was used for modeling, which is capable of simulating in both agent-based and system dynamic models. Enjoying a desirable graphical environment, AnyLogic has witnessed a lot of changes due to its wide use in different fields [14]. Modeling in this software consists of defining the simulation environment, generation of populations or agent groups, developing diagrams of agent performance to represent the states of each agent, formulating behavioral rules and functions, and implementing the model(s) obtained.

3. Study region

Covering an area of 51442.3 km^2, the Zayandehroud Basin is bordered by the Salt Lake on the north, the Great Karoon River Basin on the west, the SiyahKooh Desert Sub-basin on the east, and the Sirjan and Mahgarloo Desert Sub-basin on the south. The study region in this basin is the Lenjanat (4209) sub-basin located between 51° 2' to 51° 52' east longitudes and 31° 45' to 32° 31' north latitudes. It covers an area of 3365 km^2, out of which 1619 km^2 is plain land housing Mobarakeh, Lenjan, Zayandehroud, Baghbahadoran, and Talkhooncheh towns. The exit surface flow of 1359.2 MCM from the Bon-Saman Station accounts for the only surface flow into this region, part of which is allocated to domestic and industrial uses. The remaining 535.5 MCM forms the outflow from this region into Najafabad region [30].

Fig. 5. Location of Lenjanat sub-basin in Zayandehroud Basin

Ground water in the region is extracted through 543 Qanats and 3760 water wells, with 2355 being legal and the rest being illegal wells. From the total number of wells dug, 935 are operating while the rest are non-operational. The total volume of ground water abstracted in the region reaches 244.1 MCM, 172.3 MCM of which is extracted through the operational wells.

The annual volume of water used by the agriculture sector in Lenjanat amounts to 387.2 MCM, out of which 197 MCM is supplied from groundwater resources and the remaining supplied from surface flows. The hydrograph of Lenjanat aquifer in Fig. 6 shows that the aquifer experienced an annual drop of 0.27 m in its water table and a total drop of 5.9 m over the period from 1991 to 2016 [37].

Around 38% of the wells in the region are illegal, only some of which have been decommissioned and plugged by the Regional Water Authority of Mobarakeh Town. In fact, a large portion of the time and energy of the water resources management body in this area is devoted to the control and surveillance of water wells, especially the illegal ones. This will be dealt with in more detail in the section on behavioral modeling.

Fig. 6. Fluctuations in water table over a 22-year period

4. Results and discussion

According to Fig. 4, the stakeholders (St), regional water authority (RWA), and the public prosecutor's office (PPO), as agents, change from one state to another through time and with changes in their behavior. Changes in state might take place over long periods of time as a result of the complex relations and interactions among groups of agents. In this study, interviews were held with experts and data were extracted from the available dossiers in order to determine the time required for each change of state. Using such information, the processes were identified and the time for the transition from one state to another was determined. The following assumptions were made in these studies:

1. The durations for changes of state are derived from past experience and expert views.

2. The decision-making process reflected in the relevant agent state diagrams are based on the characteristics of WRA, St, and PPO; moreover, the decision-making and the time requirements would not change throughout the simulation period unless under the effect of different scenarios.

3. The time determined for each change of state is based on the average time observed for that particular change of state.

4.Relations and interactions among the agents in the model are accomplished through a messaging system.

5. Only one RWA and one PPO with 1359 St agents are considered and these numbers remain constant throughout the study period.

6. Two scenarios are set up with the three parameters of "meetings with public organizations", "enhanced experiences and strict law enforcement", and "strengthening patrol teams". In the first (inefficient) scenario, none of these parameters are functional while they are in the second (efficient) one. The effects of these parameters are recorded as the result of interactions of RWA with other public organizations and their meetings after the adoption of "Groundwater Resources Reclamation and Balance Scheme" in 2015 as well as increased experience, strict law enforcement, and strengthening patrol teams after 2016.

7. The process depicted in Fig. 4 is a linear representation while causal and chronological orders in a system are of great significance (in the sense that RWA initially submits a report, the St reacts to the report, and then the PPO enters the scene before RWA embarks on a second round of actions). In order to determine the effects of the above three parameters, they were independently introduced into the first scenario but removed from the second so that their effects could be determined independently from each other.

8. The framework adopted and its procedure in Fig. 4 were based on the review and study of several lawsuits on water issues in the study region which were used in the simulation.

9. Given the fact that the short-term objective of the third directive was to restore a zero water balance after a period of 5 years, the length of the simulation period was selected to be 5 years (60 months).

10. Based on the information and reports available at the RWA in the study region, each illegal well has a specified discharge rate that is taken as the St agent's characteristic in the agent-based model. When an illegal well is decommissioned and plugged, the behavioral model declares it as nonoperational, withdrawal from that well will become zero in the systems dynamic model, and its effect on the groundwater resources system is then determined.

11. To determine the reasonability of the time predicted for the decommissioning and plugging of illegal wells in the "Groundwater Resources Reclamation and Balance Scheme", the scenarios devised are continued up to the time this is accomplished and then the time taken is compared with the 5-year period predicted in the project.

4.1. Model calibration and verification

The calibration and verification of agent-based and hyrologic models typically face serious challenges due to the complexities inherent to such models [19]. These challenges stem from the complex human behavior and the unavailability of data and information on social issues.

The processes employed in the model developed in the present study were based on the data observation wells, reports of Regional Water Authority and information extracted from water-related lawsuits and interviews with experts. The data used in the 28 months of model calibration and 8 months of verification were extracted from the lawsuits filed over the period from 2006 to 2009 (36 months). The results are reported in Fig. 7.

Fig. 7. Results of model calibration (28 month) and validation (8 month)

4.2. Results obtained from the scenarios

Scenario 1 (inefficient): It is assumed in this scenario that RWA and the public prosecutor's office would interact in the same fashion as they did during the time prior to the adoption of the "Groundwater Resources Reclamation and Balance Scheme", meaning that they would exercise no serious control and surveillance. In other words, this scenario is based on the assumption that the decision-makers and public organizations attach great importance to stakeholders' satisfaction. The continued dissemination of this policy and its practice through time have led to RWA's declining authority and power and their failure to protect resources.

As a result of this policy, water resources have been left in derelict, laws and regulations have been forgotten, stakeholders have learned to ignore notices, and they have even shown resistance against official policies and regulations. Hence, these processes are absent from the simulation under this scenario.

Fig. 8 illustrates the execution of this scenario over a period of 60 months (2011–2016). Clearly, the treatment of violations of law begins from filing a report, receiving orders from the central office, and submission of a complaint to the public prosecutor's office. Hence, the numbers of violation reports, court decisions issued, and illegal wells decommissioned and plugged shown in this Figure are extracted from the simulation model. According to Fig. 8, 403 violation reports were confirmed for 166 of which court decisions were issued, 142 illegal wells were decommissioned and plugged by RWA, and 24 wells remained unplugged. The lack of experience and poor law enforcement on the part of the surveillance body, the rather long court process time at the PPO, the poor understanding and knowledge of water regulations and water resources among the relevant public organizations, and, most importantly, the low importance attached to violations of laws pertaining to water resources are among the factors responsible for the long and slow process of and the difficulty in handling violations. Despite the rather large number of violation reports (404), only 166 cases (41%) were completely addressed and 24 cases (about 6% of the total violation reports) led to no final decisions due to the inefficiency of RWA staff members, the stakeholders' strong resistance, and the failure of the public prosecutor to issue final decisions. Also, Fig. 8 shows fluctuation in water tables that has been decreased 1.5 meter over a period of 60 months.

Fig. 8. Results obtained from the AnyLogic under scenario 1

Scenario 2 (efficient): This scenario is based on the assumption that violation control takes an increasing speed adopted in the study region since 2016. The reasons for this increased pace in controlling violations include the adoption of the "Groundwater Resources Reclamation and Balance Scheme" and the stringency shown by the Ministry of Energy in executing this scheme, learning from past experience, holding meetings with the public prosecutor's office, and strengthening patrol teams. Thus, these parameters are operational under scenario 2. The results obtained are reported in Fig. 9. Similar to scenario 1, this second one was also executed over a 60-month period during which time 1335 violation reports were confirmed by RWA for 996 of which verdicts were issued by the public prosecutor's office. During this period, RWA was able to decommission and plug 935 illegal wells (70% of the total wells) while 51 (accounting for only 2% of the violation reports) remained operational.

The meetings with the PPO held by RWA not only raised among them an awareness of the critical conditions of water resources in the region but also attracted their enhanced cooperation. Another advantage of these meetings was accelerated settlement of the cases. These meetings also led to a common understanding and enhanced interactions with the public prosecutor's office so that a five-fold increase was observed in the number of case settlements during the 60-month study period while the time lag between filing a violation report and a final court settlement also reduced (Fig. 9). Moreover, RWA hired new staff members, which obviously enhanced their law enforcement powers and, compared to the situation under scenario 1, reduced the time taken to plug and decommission illegal wells after a court decision was announced. Also, Fig 9 shows water tables that has been decreased 0.5 meter over a period of 60 months that is better that scenario 1. The sections below provide a more exact comparison of the two scenarios, a description of the present situation, and an analysis and evaluation of the parameters involved.

Fig. 9. Results obtained from the AnyLogic under scenario 2

4.3. Comparison of the two scenarios and the present situation and analysis of the parameters

Fig. 10 below shows a very slow trend in violation control in the study region up to the end of 2014 so that only 34 illegal wells had been plugged by the end of that year. At the beginning of 2015, however, the trend in the simulation is seen to be reversed and violation control to gain momentum so that the number of plugged illegal wells reached 534 by the end of 2016. Violation control in the first scenario followed a trend by 2014 quite close to the current one. However, the activation of the parameters discussed above (holding meetings with other public organizations, strengthening patrol teams, and enhanced experiences gained) led to the greater current performance in violation control than that in scenario 1. The assumption in scenario 2 is that all the parameters are activated from the very beginning and, thus, violation control takes a high speed from the very first day so that it is far more enhanced than those in the current state or in scenario 1.

Fig. 10. Comparison of the two scenarios in terms of their performance in violation control

Groundwater resources in this study are modeled using the systems dynamic model. Fig. 11 depicts the aquifer water table throughout the simulation period for the current state and under the two scenarios. Cleary, water table throughout the simulation period is by 0.3 meter higher in scenario 2 than it is in the current state and by 0.7 meters higher than that under scenario 1.

Fig. 11. Water tables and renewable storage of aquifer under the efficient and inefficient scenarios compared with the current state

Table 1 Comparison of numbers of plugged wells and renewable storage

Table 1 reports the same results for the two scenarios and the current state. Based on the review of the lawsuits and the information therein as well as interviews with staff members of regional water authority of the study region (Lenjanat Regional Water Authority), the main parameters affecting violation control were found to include “meetings with other public organizations”, “learning from past experiences and strict law enforcement”, and “strengthening patrol teams of law enforcement”. To explore the effects of each parameter, they were separately introduced into scenario 1 and subsequently simulated at each step to determine the positive effect of each. In scenario 2, the parameters were removed one by one and simulated at each step to determine the negative effect of each parameter.

Table 2 Investigation of the effects of the parameters on the number of plugged and decommissioned wells

Clearly, the parameter “holding meetings with public organizations” was the most effective one in all cases while “strengthening patrol teams” in scenario 1 and “enhanced experience and strict law enforcement" in scenario 2 had the least effects. Considering the fact that the issuance of court sentence and coordination with the public prosecutor is of the greatest importance in violation control, it may be said that the water authority staff members were able to achieve a considerable success in violation control following consecutive meetings and coordination with the prosecutor. Fig. 12 depicts the effects of the parameters on renewable storage investigated.

Fig. 12. Contributions of the parameters due to their introduction or removal from the scenarios to water table

According to this Figure, renewable storage in the aquifer declined by 51.6 MCM when the parameter "meetings with public organizations' was removed but it led to a rise of 9 MCM in renewable storage when it was introduced into scenario 1.

The two scenarios were independently implemented to investigate the feasibility of executing the "Groundwater Resources Reclamation and Balance Scheme" and to determine the time required for plugging and decommissioning all the illegal wells under both scenarios. The results indicate a time requirement of 426 and 101 months under scenarios 1 and 2, respectively. In other words, under the best conditions, at least 101 months would be needed to achieve part of the short-term objectives of the scheme.

5. Conclusion

The present study mainly aimed to simulate the violation control and surveillance within the Lenjanat region and to assess the parameters involved. The parameters in question emerged from interactions of RWA with other public organizations, adoption of regulations to accelerate court procedures, raising awareness of the critical conditions of water resources, and changes in the behaviors of RWA and other public organizations involved. In this study, the AnyLogic software was used for simulating the behaviors of the different agents involved. For this simulation, two scenarios were also defined to investigate the effects of the parameters in question. Results revealed that RWA was able to achieve success under the current laws and regulations in its management of water resources and especially in its control of violations of law if it enters into appropriate and effective interactions with the public organizations involved. Investigations also showed that, under the present regulations, if changes are affected in the behavior and interactions of RWA (scenario 2), it would be able to increase 55.2 MCM of the renewable storage and lead to a rise of 0.7 meters in water table over a five-year period.

Another aspect of the study involved the investigation of the parameters affecting violation control. Results revealed that the parameter “holding meetings with other public organizations” had negative or positive effects of –9 to 51.6 MCM, respectively, on renewable storage.

Based on the short-term objective of the “Groundwater Resources Reclamation and Balance Scheme”, the model was executed under two different scenarios and the time to achieve this objective was determined under each scenario. In the best conditions (i.e., scenario 2), it was found that around 101 months would be needed to realize one of the objectives. The reason for this lies in the nonexistence of the required conditions and the failure of the stakeholders to cooperate toward these objectives. On the other hand, the reliance of stakeholders for their jobs and livelihood has led to leniency on the part of public organizations with respect to law enforcement.

For future research, the parameters affecting the behavior of both stakeholders and other agents are suggested to be identified and used to forecast stakeholder’s behavior. For instance, one such behavior might be the way stakeholders would behave after wells are plugged and decommissioned. Given the conditions, they might opt for migration to other regions or exploit other illegal means and methods to maintain their agricultural production. It is imaginable that they might react in different ways depending on their different goals. However, as plugging illegal water wells leaves great impacts on the livelihood of farmers in the region, it might be necessary to amend or supplement the “Groundwater Resources Reclamation and Balance Scheme” with directives that provision the creation of water markets, opportunities for farmers to purchase water, and establishment of new industries with low water demands or those with the potential to reuse return effluents.

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Table 1 Comparison of numbers of plugged wells and renewable storage

State	Current	Scenario 1	Scenario 2
Plugged and decommissioned water wells	535	142	938
Renewable Storage (MCM)	148.5	127.6	181.8

Table 2 Investigation of the effects of the parameters on the number of plugged and decommissioned wells

	Current conditions	Introducing each parameter into the first scenario / Removing each parameter from the second scenario		
		Strengthening patrol teams	Enhanced experience gained	holding meetings with other public organizations
First	142	195	238	276
Second	938	303	704	253

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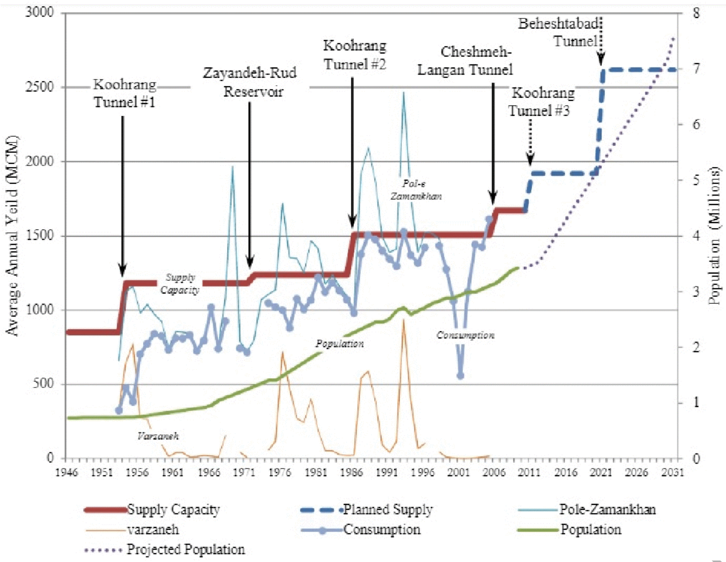
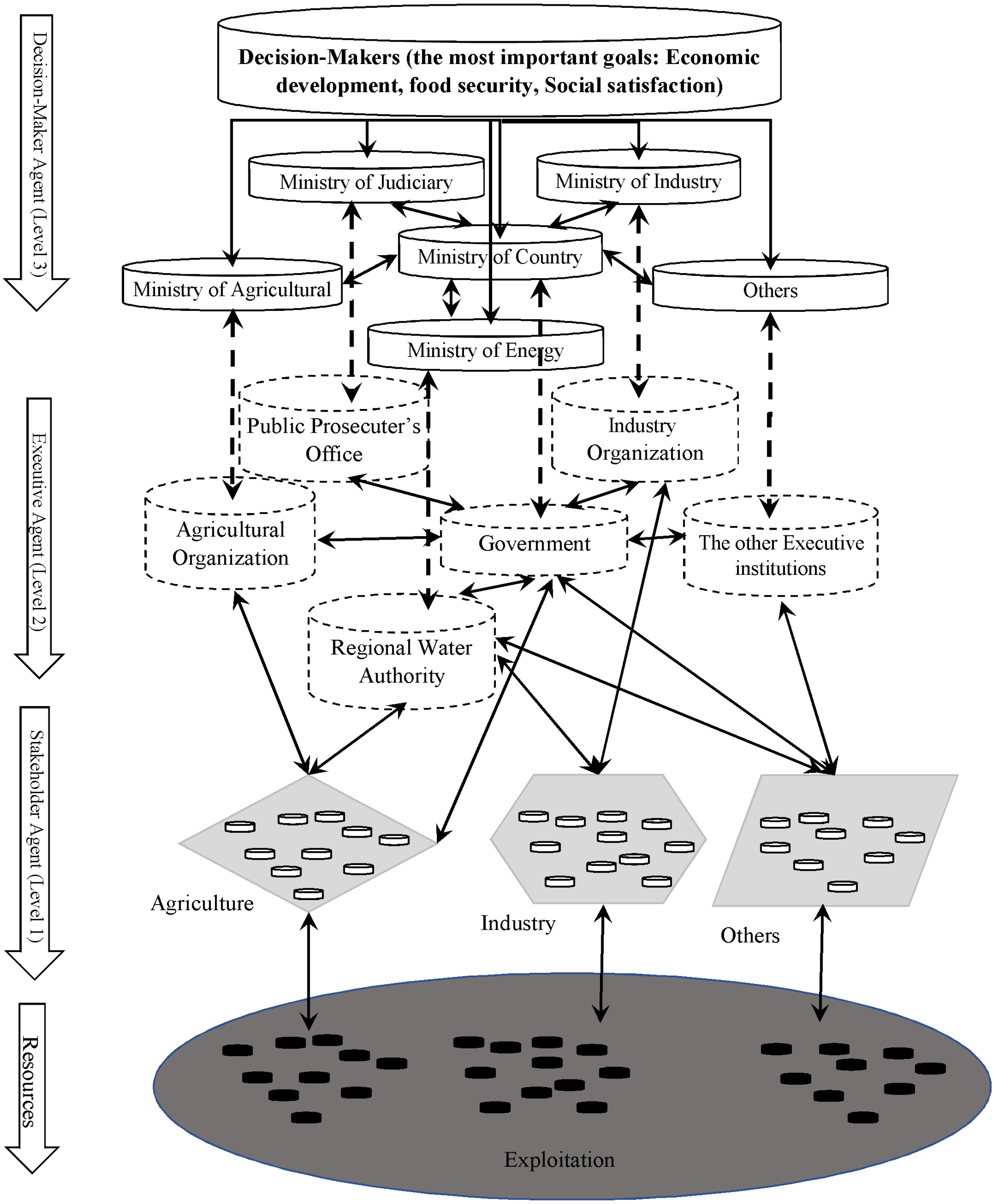


Fig 1. Development of ZayandehRood river basin water resources and water consumption



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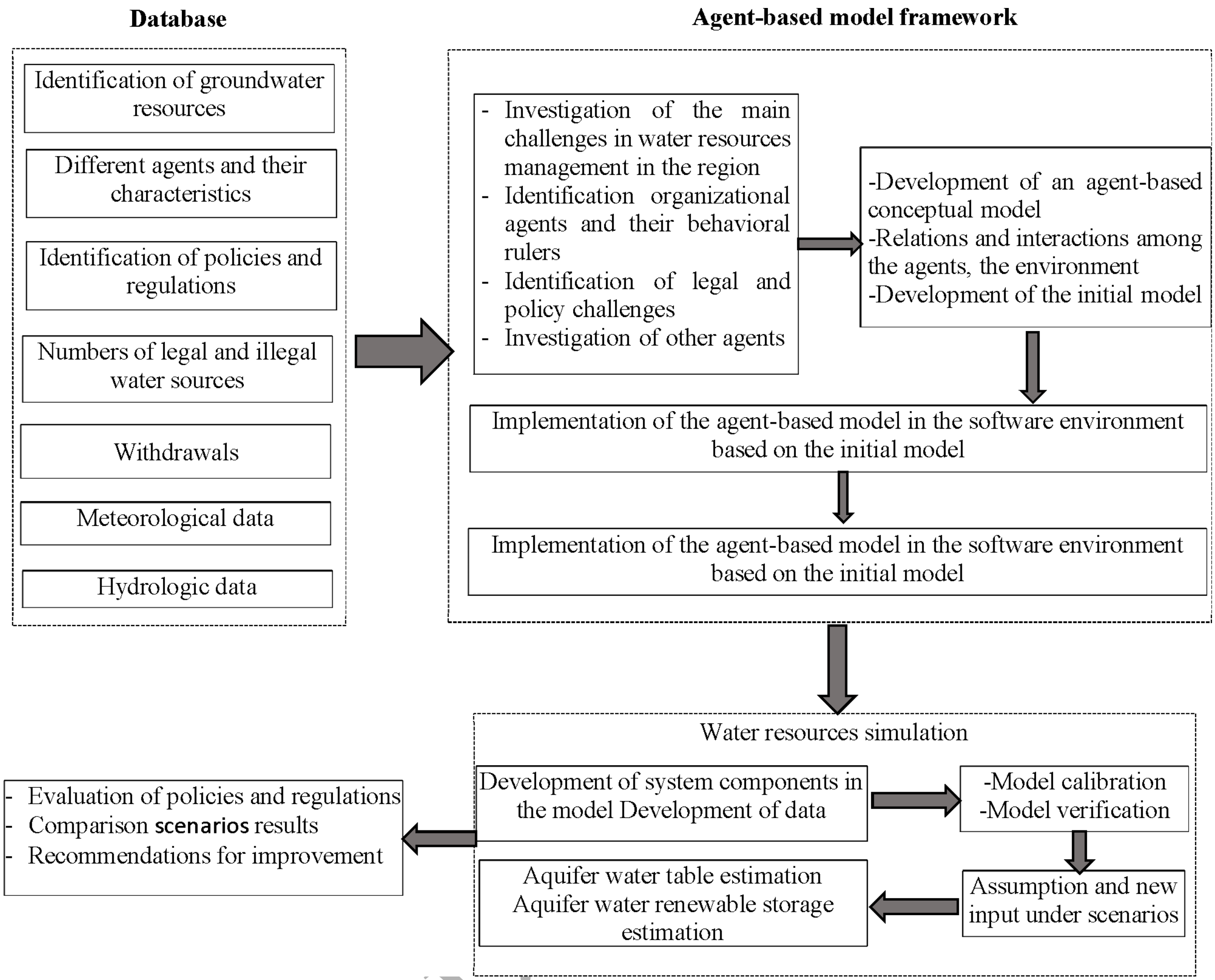

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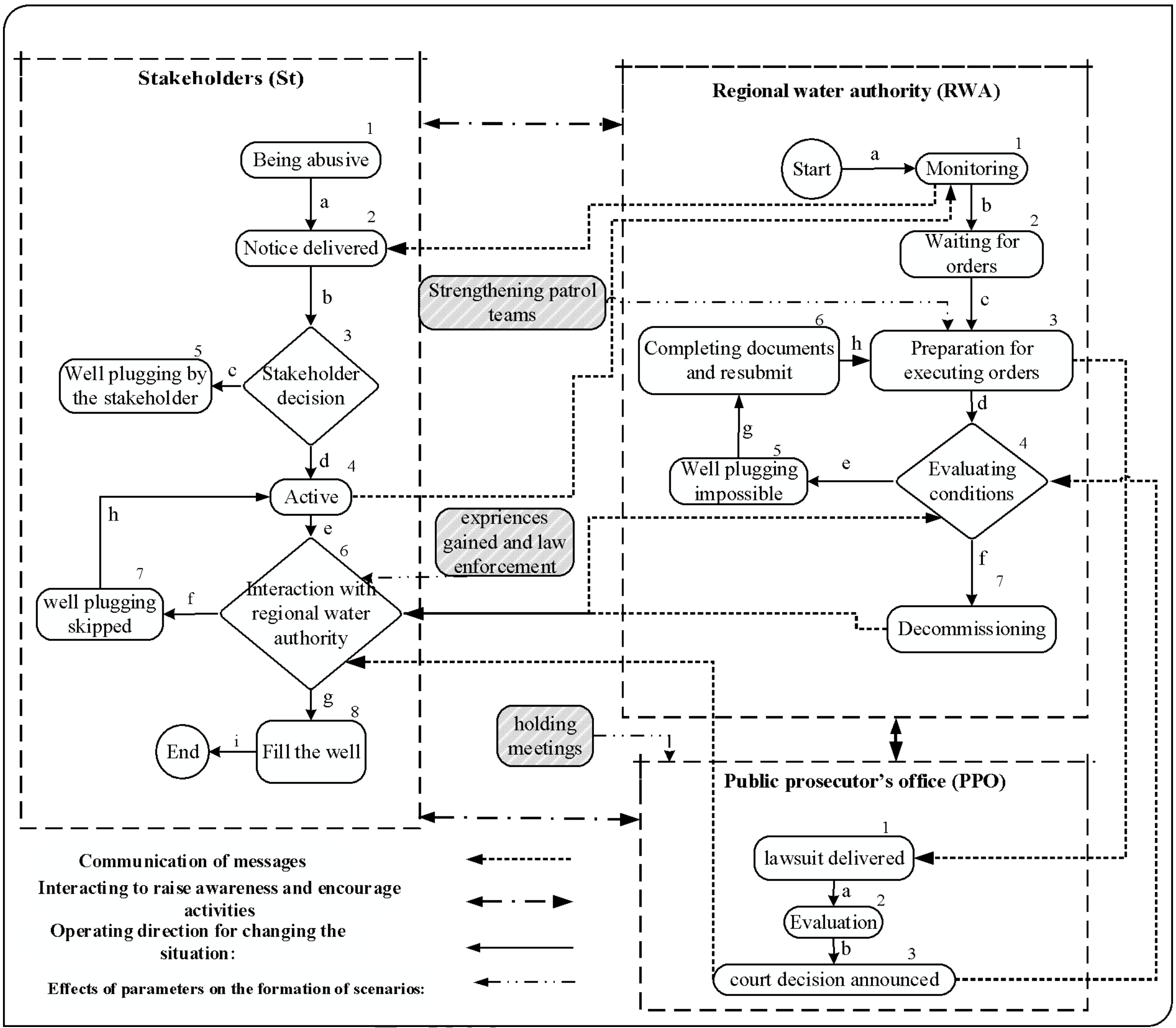

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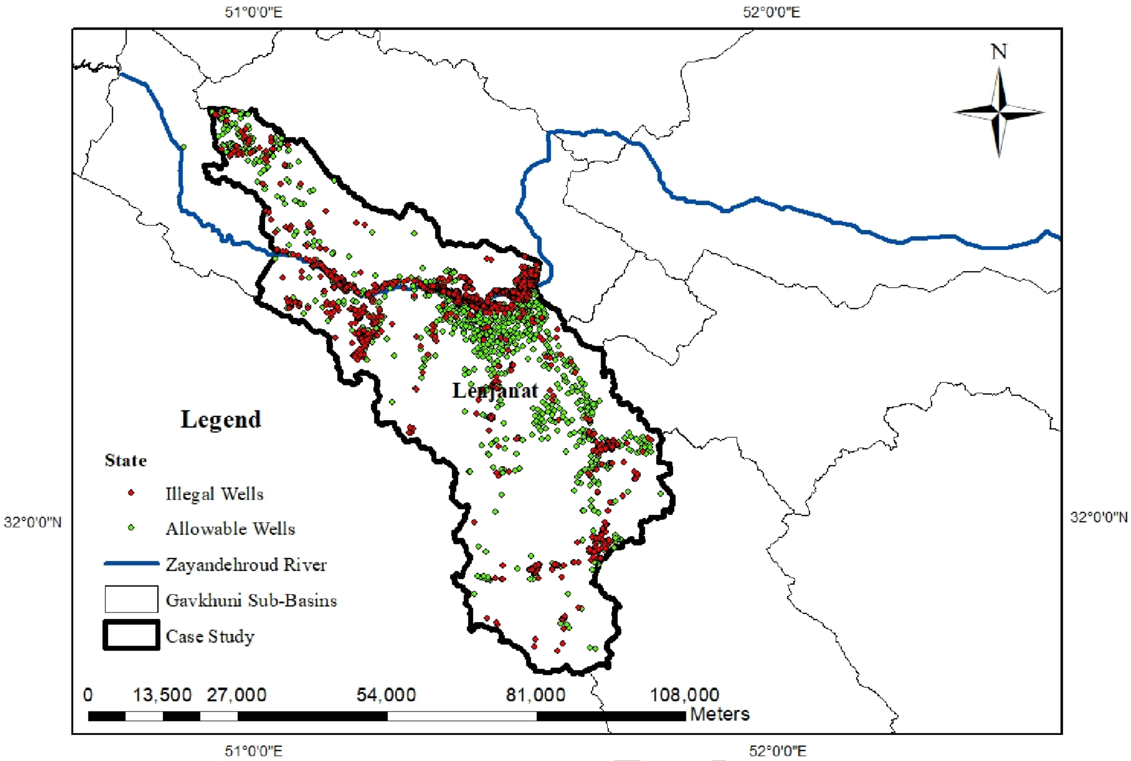

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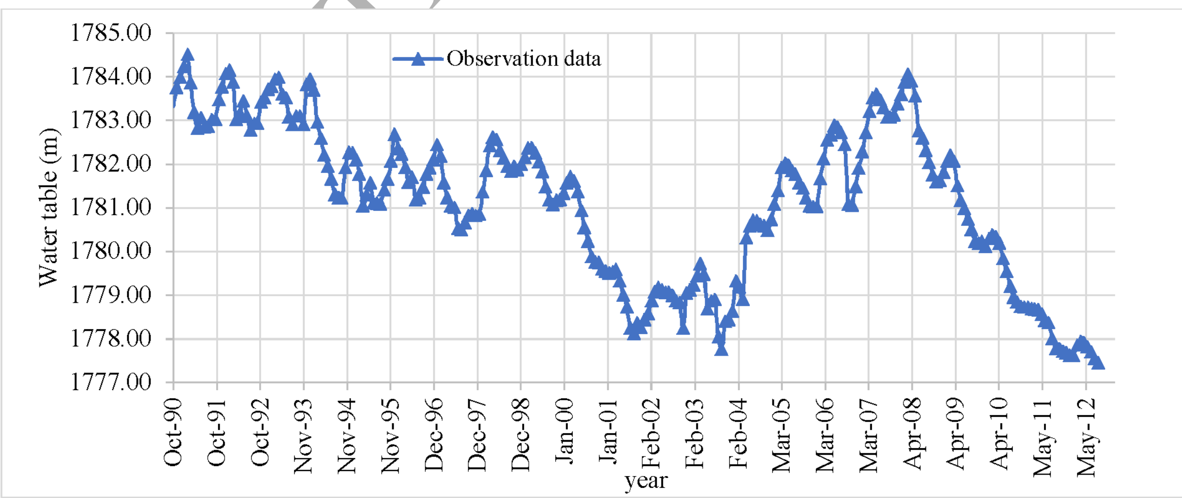

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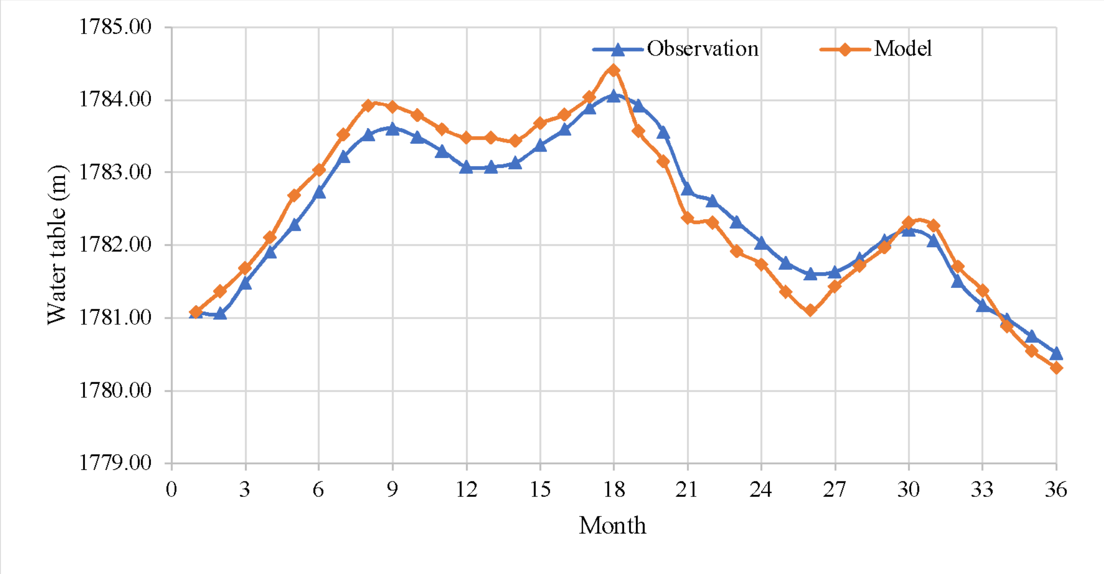

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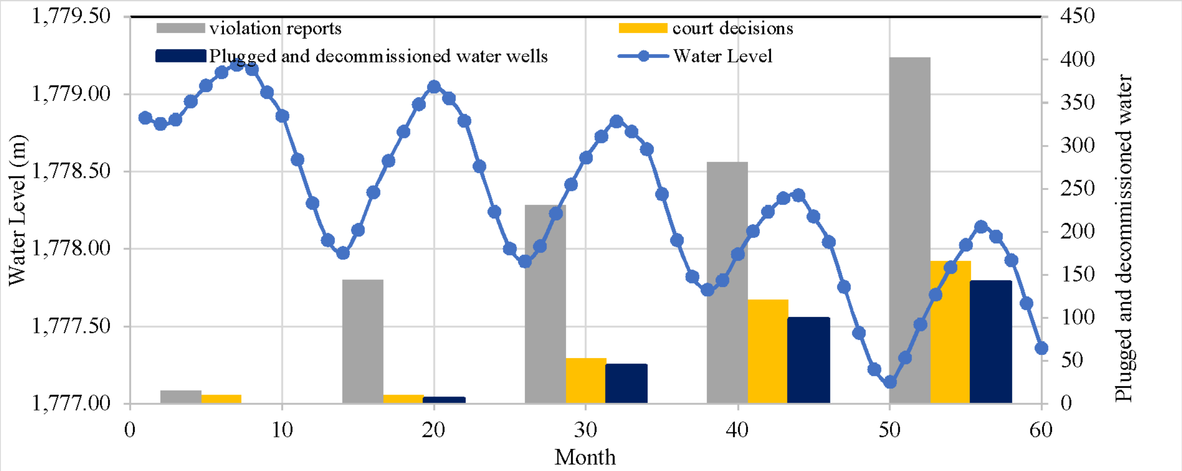

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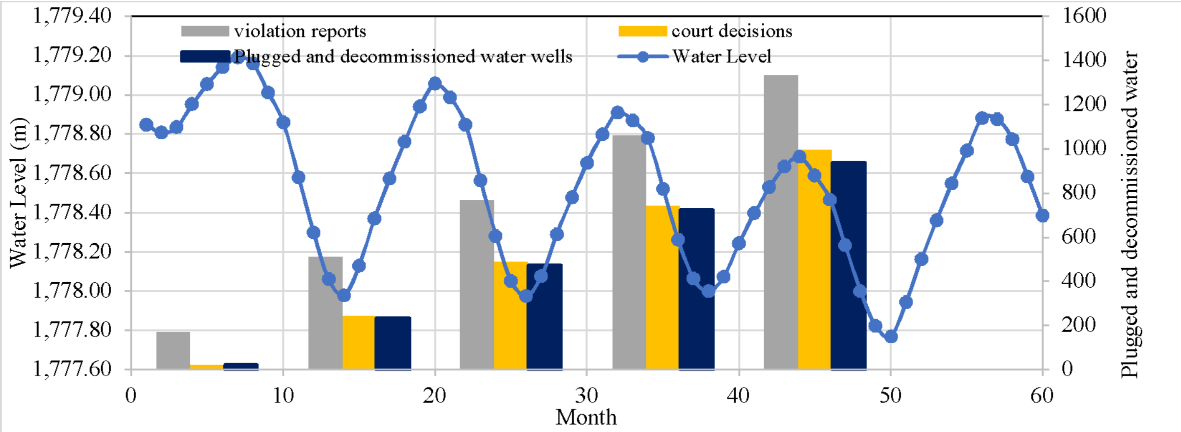

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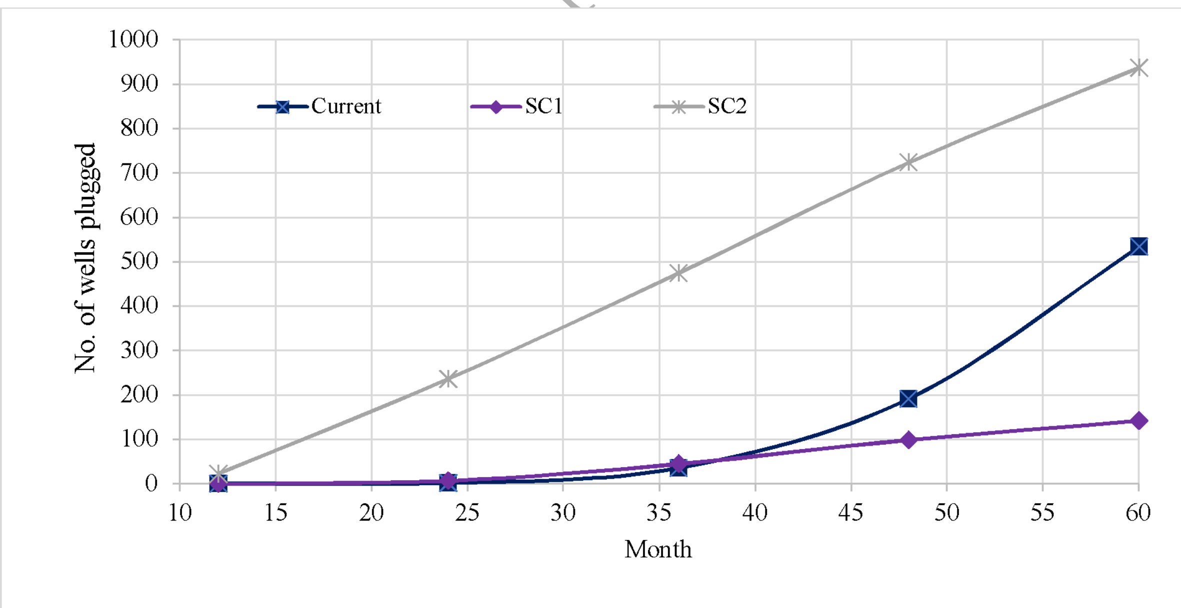

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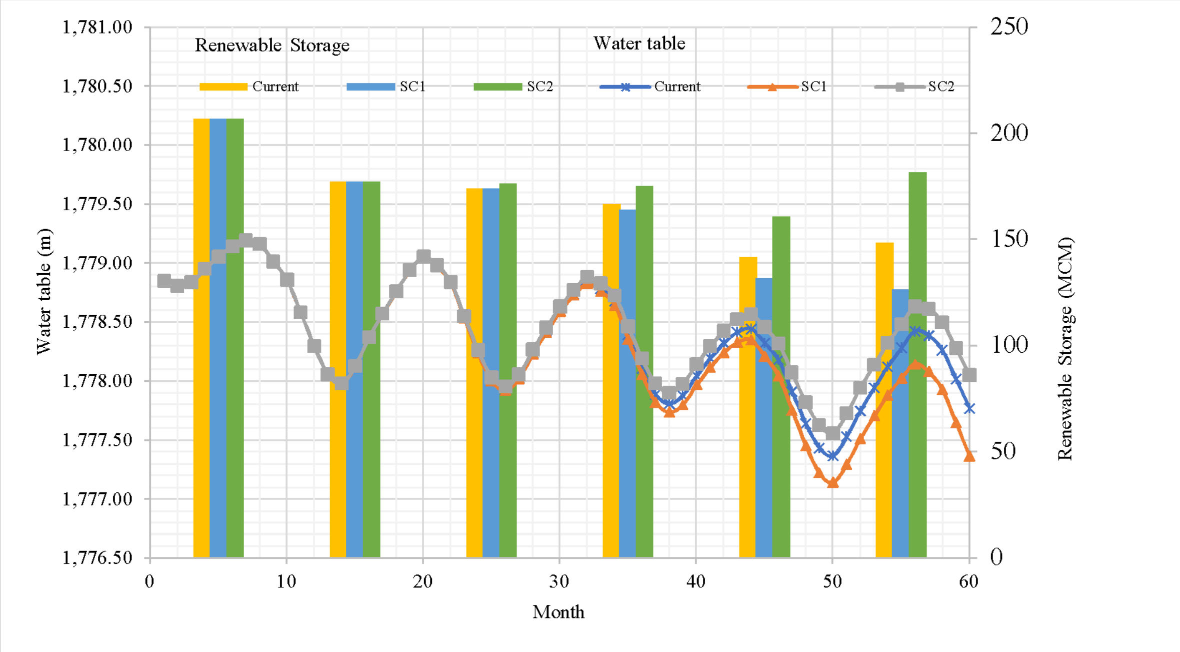

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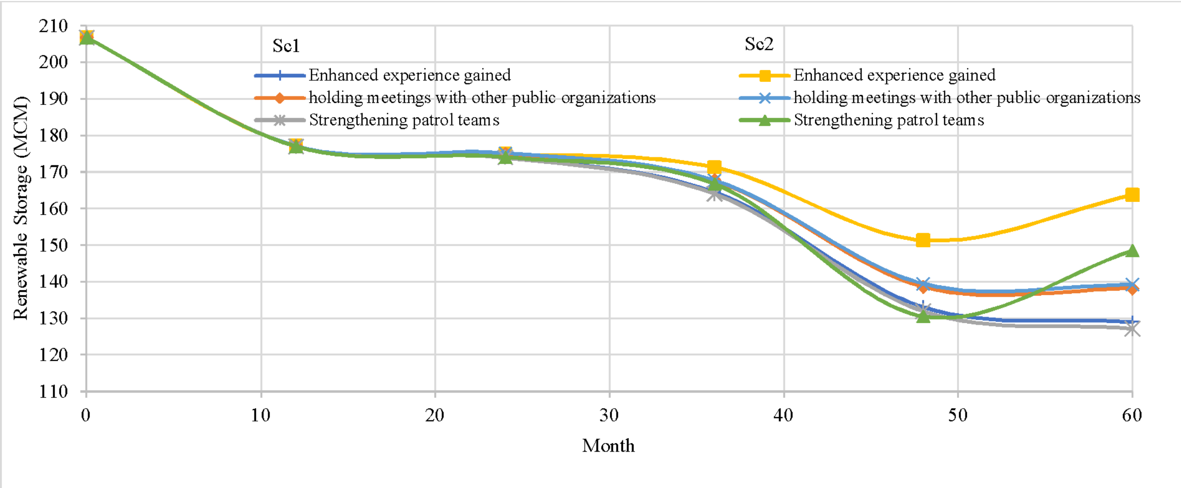

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