Using Agent Base Model for managing the critical situation of groundwater resources and aquifer balancing (Case study: Iran-Qazvin Plain Aquifer)

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Abstract.- The main purpose was to reduce the evacuation of aquifers in the Qazvin plain and then to compensate for the deficit of the cumulative reservoir and remove the annual reservoir deficit, no reduction in the revenue of farmers, and similarly to prevent the reduction of crop production. The model was developed and calibrated. In the following, the desired scenarios were implemented by the model. After providing the raw output of the model, these outputs were processed and prioritized based on the results extracted from the desired scenarios. This study applied objected-oriented modeling and Matlab software, which had a high potential in working with large amounts of data. Based on the model, output, and analysis of the results, the best scenario in the first stage was removing the unauthorized wells and preventing the excessive withdrawal of authorize wells. But, as these measures would be countered with farmers' resistance, there should be other measures such as increasing the guaranteed purchase price of products and increasing irrigation efficiency in order to prevent a sharp decline in their revenue and consequently to achieve a result.

Keywords: Agent Base Model (ABM); balancing; groundwater.

Uso del modelo basado en agentes para gestionar la situación crítica de los recursos de aguas subterráneas y el equilibrio de los acuíferos (Estudio de caso: Acuífero de la llanura Irán-Qazvin)

Resumen.- El objetivo principal de la investigación fue reducir la evacuación de los acuíferos en la llanura de Qazvin, luego compensar el déficit del reservorio acumulativo y eliminar el déficit anual del reservorio, sin reducir los ingresos de los agricultores y de manera similar para evitar la reducción de la producción agrícola. El modelo fue desarrollado y calibrado, y a través de éste fueron implementados los escenarios deseados. Después del procesamiento a través del modelo y de obtener resultados crudos, estos se procesaron y priorizaron en base a los resultados extraídos de los escenarios deseados. Este estudio aplicó modelado orientado a objetos y el software Matlab, que tiene un gran potencial para trabajar con grandes cantidades de datos. Basado en el modelo, salida y análisis de los resultados, el mejor escenario en la primera etapa fue la remoción de pozos no autorizados y la prevención del retiro excesivo de los autorizados. Pero, dado que estas medidas se contrarrestarían con la resistencia de los agricultores, debería haber otras recomendaciones como aumentar el precio de compra garantizado de los productos y aumento de la eficiencia del riego para evitar una fuerte caída de sus ingresos y consecuentemente lograr un resultado.

Palabras clave: Modelo basado en agentes (MBA); equilibrio; agua subterránea.

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1. Introduction

Groundwater resources over-exploitation in Iran leads to a reduction in the volume of water stored in aquifers, reduction in groundwater quality, the striking the especially in the desert and coastal aquifers, saltwater fronts, subsidence, seams, cracks, sinkhole, damage to infrastructure facilities and in important plains of the country and an increase in the deepening and moving the wells. Consequently, under the influence of the condensation of the aquifers and the destruction of the porosity, even in case of rainfall, there is no possibility for water penetration and storage in the aquifers. The total level of Iran is grouped into 609 study areas concerning the catchment area. According to the Water Resources Management (WRM) organization, a sharp decline in groundwater levels and the aquifers' reservoir deficit resulted in banning the 420 of the above 609 regions based on rules to expand the exploitation of groundwater resources [1].

The ABM approach is an appropriate tool for modeling complex systems and phenomena in which the behavior of people or institutions is significant. In this modeling approach are modeled the actors (agents) and their behaviors concerning themselves and their environment. They are used to measure the effectiveness of the behavior of different actors in the system and their interaction with their environment on the overall behavior of the system. The potential features of the ABM approach for facilitating the participation process and improving its quality were of utmost discussion in the water resources management in recent years [2].

ABM approaches, by use of simulating the consequences of people's behavior, can be considered as a remarkable help in the conventional analytical approaches for investigating environmental problems [3] and presenting the visual framework for studying social and ecological variables [4]. Considering two social and ecological dimensions or the users and the water resources system, this model makes it possible to deal with water resources management issues with more realistic and take action in stabilizing water resources. In ABMs, the participation of authorities is regarded as a vital element [5]. The bottom-up approach applied by ABM was critical in investigating the socio-environmental systems [6, 7]. This computational model was used for simulation and adopted from the research fields of artificial intelligence and cellular automata [8].

However, the interaction between environmental and social variables in the ABM might be greatly simplified [9]. The interaction between agents was usually considered based on time and environmental and social variables [10]. A combination of social and natural science methods was needed to properly study the dynamics of social and environmental subsystems and examine environmental and social variables [11, 12]. A comprehensive study of the complexity of environmental, social, and economic systems might be required an interdisciplinary approach [13]. Many studies were conducted on the relationship between physical models of environmental systems and simulations based on social process factors. Some of those studies were conducted by [14, 15].

ABM techniques had a person-centered approach in which each user had their own behavioral rules. Each user could make a change in the behavior regarding the information received from other users and the environment. Moreover, users did not need to share the whole information with others [16]. The limitation of the ABM model was that its forecast was always conditional, depending on the conditions set forth in the model. In [17] allowed the possibility of decision-making concerning dynamic behaviors of agents interacting with each other and their environment [18, 19]. The ABM was able to simulate the human decision-making process by specifying the behavior of the agents.

The ABM is a decision-making support tool and could offer water resources protection measures by various scenarios and assumptions [20]. The application of ABM approach in the water resources management was begun from one decade ago and became a popular topic in the analysis of natural-human systems [21, 22, 23, 24, 25, 26, 27, 28, 29, 30].

The opinions should be cautiously designed to increase the value-added result using ABM in land and water management [31]. The ABM was applied to forecast the urbane household water demand in Beijing in 2020 [32]. Furthermore, this model simulated urban water dynamics [33]. Nouri [34] attempted to simulate the rules of the system in the form of mathematical relations concerning the interaction between agents such as the environment and agriculture.

The ABM approach was observed in the different areas such as archeology, biology, economics, environment, electricity market analysis, financial analysis, social sciences, transportation system and water management system [35, 36, 37].

Lately, ABM models were offered as a proper factor in terms of describing the processes of using innovation in the area of energy and electronic resources [38, 39] and known as a popular tool in the scientific community to manage the problems raised by the natural human system [40].

ABM models were taken into consideration as a powerful tool for modeling complex systems [41]. Applying this approach facilitated the consideration of two general social and ecological sectors as well as their mutual influences. The social sector in this approach encompassed all users or actors who were under the influence of the system and also affected the system. The ecological sector in this approach consisted of all of the sub-models that formed water resources and their related systems. Nothing limited the definition of the social and ecological sector and the relationships between them in the modeling approaches. The only weakness and restrictions were observed in the data and field information. The most remarkable strength of this modeling approach was observing the social sector in the model along with ecological sector as well as regarding their relations and interactions [42]. Actually, the principal idea of this approach was to close the model to the real situation of the problem as much as possible and consequently obtain more realistic results from the model. This was way the use of ABM modeling was significantly increased in the field of modeling the complex systems, especially complex water resources systems [21].

ABM modeling and its use in water resource systems between them and the environment and the communications of the set of agents located in it formed the components of an ABM. Moreover, agents interacted with their environment [36]. Then, it was possible to illustrate individuals, organizations, and their activity environments as multi-agent systems (MAS) and utilize ABM approach.

The unsuitable condition of groundwater resources in Iran, resulted by incorrect management, excessive aquifer withdrawal in Iran and successive droughts, led to numerous problems including subsidence, water salinization, increasing the depth of water table and consequently increasing the required energy consumption for water extraction and social consequences such as forced migration from motherland and suburbs in large cities. Different strategies were proposed by the authorities to therapy this matter, but it must be in such a way to entail maximum effectiveness and have minimum consequences. The ABM was a modern model considered for problem-solving, used in examining the proposed scenarios by observing all limitations and weaknesses and strengths. Through ABM, it could be select the best scenario to solve the problem of groundwater. This study selected Qazvin plain as a pilot, which was located in central regions of Iran, and its agriculture was highly dependent on groundwater resources.

2. Materials and Methods

Using the ABM was increasing for modeling different systems, especially complex socio-ecological systems of water resources. Since the agricultural sector was known as the largest consumer of surface and groundwater resources, the collection of farmers and their withdrawal of water resources were highly remarked in the conducted papers. To this end, were developed some models in order to contribute the decision-makers and users in making better decisions on their policies and cultivation patterns, profitability, resource exploitation, and sustainability. The adaptable policies in the water resources systems were categorized into three different groups [43]. The first group was technical tools to control water consumption. The use or development of the use of modern irrigation systems as well as installing the flow-meters on agricultural wells and their application were among the policies of the first group. The second group encompassed economic tools. Water pricing, tax, withdrawal fines, and the water market were among the policies embedded in the second category [26]. Finally, the third category dealt with non-economic policies, such as rules of access to water, water quotas and exploitation training [26, 44, 45, 46].

However, all policies apparently could be conductive in controlling the extraction and stabilization of water resources. In reality, there might be no necessary sanction for all of them due to the significant effect of the social sector or the users. Often, the characteristics and behaviors of water resources exploiters were in such a way that some policies would not meet their expectations. Then, these policies did not signify the sustainability of resources and also led to the destruction of water resources. It could be possible to detect the superior policies in the field of water resource management through ABM with more realism and under the conditions of the study area. For example, Feuillette [43], using their developed ABM, concluded that the condition in the area under the study was in a manner that not only subsidizing farmers for changing the irrigation system did not reduce the water resources withdrawal, but also provided the condition for cultivating more lands and hence more exploitation of water resources. Doubtlessly, the most challenging part of ABM was related to the designing part of agent behaviors. Certainly, the best kind of validation could be a combination of quantitative and qualitative methods [42].

2.1. *Groundwater system simulation*

The major environmental indicator was the groundwater resources and aquifer of the region. Concerning the fact that the goal was to balance the aquifer, the effect of the taken measures must be evident in the water table changes. Bear [47] conducted the groundwater flow equation in transition mode as follows in equation (1):

$$\nabla.(K\nabla h) = S\frac{\partial h}{\partial t} \pm Q \qquad (1)$$

In this equation ∇ was the hydraulic slope, K was hydraulic conductivity, h was the height of the piezometric level, Q was the depletion rate from the aquifer, and S was the coefficient of the storage. In this study, a groundwater model named Modflow was examined and applied to investigate changes in the piezometric surface of the aquifer in the region. This model was implemented over and over, and the decisions were made considering its outputs on the impact of different scenarios implementation. In this model, farmers were observed as those who had groundwater rights. Also, environmental right, as a portion of the environment from groundwater resources, was seen as farmers' right and should be retained. With the help of Modflow model under various conditions, the allocated portion was given to the farmers in different scenarios. This interaction between humans and the environment was supposed to eventuate in a sustainable development pattern.

2.2. *Simulation of Agricultural Agent Behavior*

The farmers had a tendency towards taking maximum exploitation of water resources and having maximum possible revenue from their agricultural land. So, they resisted water withdrawal restrictions. They were reluctant to pay for the flow-meter to purchase or install and attempted to demolish and manipulate it in such a way to disable the measurement. If the flow-meter was paid, they would protect it. Farmers who were properly justified and were well-cultured and well-informed were less resistant to flow-meter installation and showed higher participation. They tended to purchase flow-meters with low-cost and low-interest facilities, but they were reluctant to give a guarantee or guarantor for the facility. If there were no other income sources, the farmers used unauthorized wells and were strongly resistant to filling wells. In cases where a large number of exploiters owned the well, this resistance was much higher, and sometimes it was impossible to fill the well. Simulation of agent behavior principle might be examined based on the considered limitations and existing rules through behavioral optimization and functional models [21]. One of the best models applied in the ABM and used in the present study was socioeconomic optimization models to maximize agent profitability [48]. On this basis, the objective function for maximizing revenue resulted by sales of agricultural products and concerning the physical and behavioral constraints was as follows in equations (2) and (3):

$$\max T_{t,i} = \text{In}_{t,i} = \sum_{i=1}^{n} Pr_{t,i,j} \cdot P_{t,j} \forall i \quad (2)$$

$$Pr_{i,j} = f_{i,j}\left(A_{i,j}, W_{i,j}\right) \quad (3)$$

In this equation, $T_{t,i}$ was the value of the objective agricultural function of the agent i during the time period of t, $In_{t,i}$ was the amount of revenue of the farmer during the time period of t (in dollars), $Pr_{t,i,j}$ was the production volume of agent i during the time period of t from j product (in ton), $P_{t,j}$ was the cost of producing product j during the time period of t (in millions of dollars per ton), $f_{i,j}$ was the objective function of the agent i for product j, $A_{i,j}$ was the area under cultivation of the agent i from the product j (in hectare). $W_{i,j}$ was the water volume used by agent i for producing product j (in 1,000 m^3 per hectare), and n indicated the number of product types. With the aim of determining the revenue resulted by agricultural production, it should be mentioned that the price of products changed based on different times and relied on the production rate by other farmers and the time of product supply. A regression model, proposed by [49], could be applied to forecast the price of the products.

$$P_t = AQ_t + B \quad (4)$$

In equation (4), P_t was the cost, and Q_t was the production volume during the time period of t.

Farmers confronted with two main limitations on crop production, one of them was the permissible water volume for exploitation, and the other was the land area they owned. These limitations were cleared in the equations (5) and (6).

$$\sum_{j=1}^{n}\left(A_{i,j} \cdot W_{i,j}\right) \leq W_{iG} \quad (5)$$

$$\sum_{j=1}^{n} A_{i,j} \leq A_t \quad (6)$$

In this equation, $A_{i,j}$ was the area under cultivation of product j by agent i and $W_{i,j}$ was the water volume used by agent i for product j. A_t was the maximum permissible area for cultivation by agent i.

2.3. Bargaining Model

Nash [50] introduced the following nonlinear optimization model with the aim of ensuring the fair allocation of resources by bargaining, by the equation (7).

$$\Omega = \max \prod_{j=1}^{n}\left(x_j - d_j\right) \quad (7)$$

Restrictions on resource availability:

$$\sum_{j=1}^{n} x_j \leq S$$

Restrictions on individual rationality:

$$x_j \geq d_j$$

$$d_j \geq 0, X_j$$

In the equation (7), Ω was the optimum solution. S, x_j, and d_j were total available and existing resources, shareholders' share of cooperation in the use of resources, and shareholders' share of resources in separate measurements (non-cooperation), respectively. j declared the participation of each shareholder and $(x_j - d_j)$ was the benefit for shareholder j from the cooperation [51, 52].

Among the Pareto optimal set, obtained from the optimization model, Nash's bargaining model was used to select a fair design of water allocation to the agents. The bargaining model found coordination between conflicting shareholders. This model developed a three-member bargain process among shareholders: Representatives, the executive sector of government, and environmental protection agencies. However, the solutions from this model indicated that shareholders considered their preferences, but they did not find the interaction between the agents and reacted with management.

2.4. Simulation of Government Behavior

The government played a role in action in the form of two ministries of energy and agriculture. The government was required to monitor and take appropriate measures to balance the country's aquifers. Monitoring measures were closing unauthorized wells, preventing overdraw of authorize wells, and implementing modern irrigation methods and the other cases. In any event, the government should reduce the yield from the aquifer and increase the water table and reduce the reservoir deficit.

The Gini coefficient was observed in economics as an indicator to represent economic inequality. Recently, this coefficient was utilized to address the fair use of water resources [24]. This coefficient was a numerical coefficient between zero and one. The number zero showed complete equality, but an increase in this number led to greater inequality. The Gini coefficient applied the "mean relative difference". The equation (8) presented the fair distribution and a maximum and minimum withdrawal limitation for each agent. Regarding the equal value for each of the exploitation wells, this equation attempted to minimize the mean relative difference of groundwater resources allocated to farmers.

$$Min\ G = \frac{1}{12N^2\overline{Q}}\sum_{i=1}^{n}\sum_{j=1}^{n}|Q_i - Q_j| \qquad (8)$$

$$Qmin \leq Q_i \leq Qmax, i$$

In the equation (8), Q_j, Q_i, Q_{max}, Q_{min}, i, and $\overline{Q}$ were the determined water value for well$_{i,j}$, water maximum and minimum related to each area, and the mean water determined for each well.

3. Study area

The study area was Qazvin with 7347 km^2 and located in the longitude of 80'and 49'to 41 and 59 degrees east and latitude of 19'and 35'to 30 and 36 degrees north in Qazvin province. Figure 1 revealed the location of Qazvin study area. The value of groundwater withdrawal, from 8471 wells, was equal to $1{,}74 \times 10^9$ m^3/yr (1,74 billion m^3 per year), 95 % of which was through agricultural wells. The status of unauthorized and authorize wells in that plain was presented in Table 1. The annual reservoir deficit of Qazvin plain in 2020 was about 160 billion m^3. The cumulative reservoir deficit of this aquifer was about 8663 billion m^3. The volume of excessive withdrawal of authorize wells and the depletion volume of unauthorized wells was 983,37 billion m^3, 514,55 billion m^3, respectively, and total depletion volume from the aquifer was equal to 1497,92 billion m^3.

The main disruptive factors in the balance between income and outcome agents of aquifers were depletion of aquifers by unauthorized wells and excessive withdrawal by wells with exploitation license, so-called overdraw.

The mean of annual reservoir volume deficit and cumulative reservoir volume deficit of the mentioned plain from 1995 to 2019 was 160 billion m^3 and 8663 billion m^3, respectively.

Figure 2 exhibited the hydrograph of Qazvin plain. Obviously, in this hydrograph, the water table of Qazvin aquifer was diminished by 31 m from 1995 to 2019, which was declined on an average of 1 m annually. As observed in this diagram, the current meter installation process, started from 2015, had not a significant effect on improving the status of the water table drop, and it was required to take a step in tackling the existing situation.

Table2 was subjected to types of products that were mostly cultivated in the area and the area and percentage of cultivation of each product. As it was cleared, the majority of agricultural items were wheat, alfalfa, and corn, and most of the garden items were grapes, pistachios, and walnuts.

3.1. Agent-based approach

The ABM approach was considered as a promising tool in order to find scientific and practical management strategies, seeking competitive interests of water resource consumers [53]. Including human characters into decision-making in an ABM and its consequences was a complicated, controversial affair [54]. Predicting numerous factors was as a result of the reaction of difficult and often impossible factors [55].

The ABM steps involved identifying the various available and effective agents, the environment in which the agents interact, the behavioral characteristics of the agents, the manner of reacting agents with each other and the environment, and

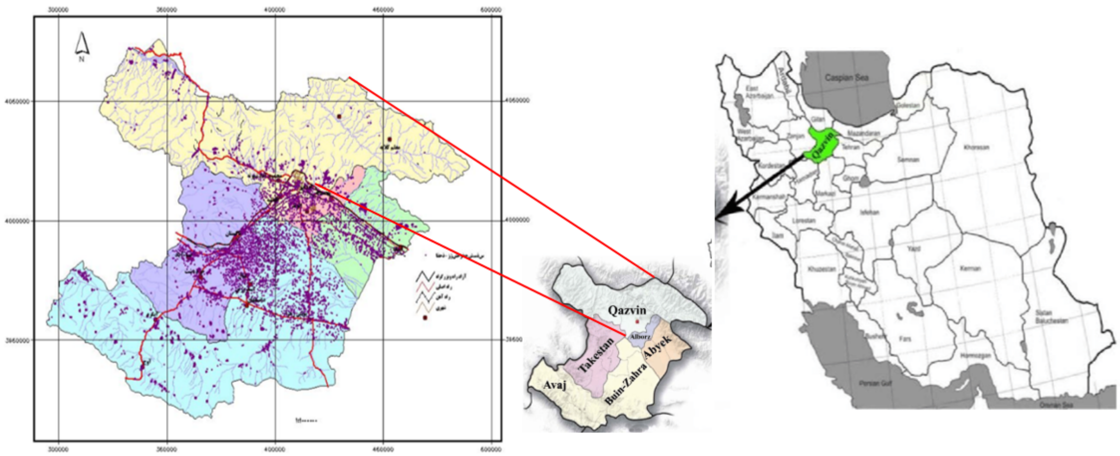


Figure 1: Qazvin study area location map

Table 1: Status of exploitation wells in Qazvin plain [1]

Kind of well	Agriculture		Drinking		Industry and other services		Total	
	Number	Depletion (mcm)	Number	Depletion (mcm)	Number	Depletion (mcm)	Number	Depletion (mcm)
authorized	2671	983.37	490	134	2231	93.2	5392	1210.6
unauthorized	2890	514.55	40	7.92	149	6.68	3079	529.15
total	5561	1497.92	530	141.92	2380	99.88	8471	11739.7

Table 2: Combination of agricultural products cultivation in Qazvin plain

The main type of use	Product type	Water need for cultivation (m^3/yr)	Cultivation (%)	Area (ha)
Garden	Grapes	10000	59	22227
	Pistachios	14500	6.5	2449
	Walnuts	17000	9.5	3579
	Other	15500	25	9418
	Total	—-	100	37673
Agriculture	Wheat	8000	35.4	46899
	Alfalfa	17000	24	28548
	Corn	12000	12.2	16163
	Other	10000	28.4	40873
	Total	—-	100	132483

ultimately implementing the model in the software environment [36].

Based on the conducted studies, the main agents could be divided into three groups: government (including the Ministry of Energy and the Ministry of Agriculture), exploiters, and the environment. The relationship between these agents was revealed in Figure 3.

These examinations were carried out in the form of questionnaires developed by farmers, informants and local authority's reports prepared by the region by consulting and information engineering companies and statistics collected from Qazvin Regional Water Company, Iran Water Resources Management Company, ministry of energy, and the negotiations with experts from the ministry of agriculture based on the BDI method. On this basis, concerning the critical situation of

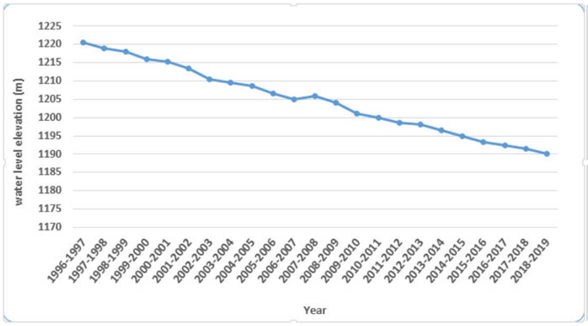


Figure 2: Qazvin plain hydrograph [1]

the Qazvin plain aquifer, the government was aimed at removing the unauthorized withdrawal and reducing the authorize withdrawal to 75 % of renewable groundwater to extract and reduce the aquifer depletion through performing "groundwater revitalization and balancing plan". To this end, authorize withdrawal limit was determined after preparing the groundwater balance and calculating the value of feeding and the aquifer depletion. However, based on international indices such as the Falcon Mark index, if more than 40 % of the volume of renewable water was used, the area would be involved in the water stress. But, since more than 100 % renewable water was currently used, the yields would be dropped up to 75 %. This measure resulted in water stress for agricultural consumers, who were the most groundwater consumers, and the farmers had to fallow some parts of their land. Farmers were also very sensitive to each other's behavior and were affected by each other's behavior. Clearly, if some farmers in the area conducted unauthorized exploitation, others would be tended to do the same. If some of them spontaneously save water, it would leave a positive impact on the behavior of other farmers. The ministry of agriculture lessened the pressure on the farmers by financial support for the implementation of new irrigation methods, such as pressurized irrigation and cropping pattern modification. On the other hand, with the increasing the guaranteed purchase price of agricultural products, it was attempted to compensate part of loss in farmers' revenue. In spite of all the government measures for minimizing withdrawals and preventing unauthorized withdrawals, some exploiters kept increasing their withdrawals from the aquifer. The government imposed fines on those who had unauthorized exploitation and increased the price of water.

In the present study, Matlab software was applied in order to model the agent behavior and prepare ABM as Figure 4. Matlab software had high capability and speed in working with huge software. After determining the mathematical equations of each agent, they were implemented in the software environment, and then the appropriate scenario was selected after several implementations of the model based on different scenarios.

3.2. Scenario Planning

The main purposes of this research were reducing depletion from the Qazvin plain aquifer and thus compensating for the deficit of the cumulative reservoir and removing the annual reservoir deficit and not significantly cutting the revenue of farmers in the area. The policies were seen into two incentives and punitive groups. Incentive groups included increasing irrigation efficiency, cropping pattern modification, and optimum cropping development and increasing the guaranteed purchase price of agricultural products. On the other hand, the punitive group included blocking unauthorized wells, preventing overdraw of authorize wells, reducing the authorize wells withdrawal, modifying their exploitation licenses, and increasing the price of agricultural water.

3.3. The Desired Scenarios

Based on the developed aims and policies for achieving a balanced aquifer, 5 scenarios presented in Table 3 could be taken into considerations. Then the best scenario was selected using ABM after implementing the model and optimizing the results.

Given each scenario, the conceptual decision-making model was prepared, and Matlab software was utilized to implement the model and select the best scenario and the effective and optimum policy in Qazvin plain.

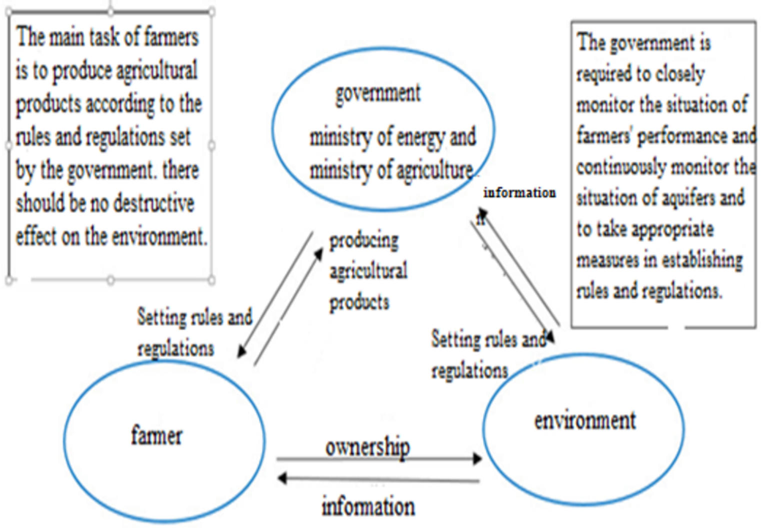


Figure 3: Conceptual model of communication between three main agents

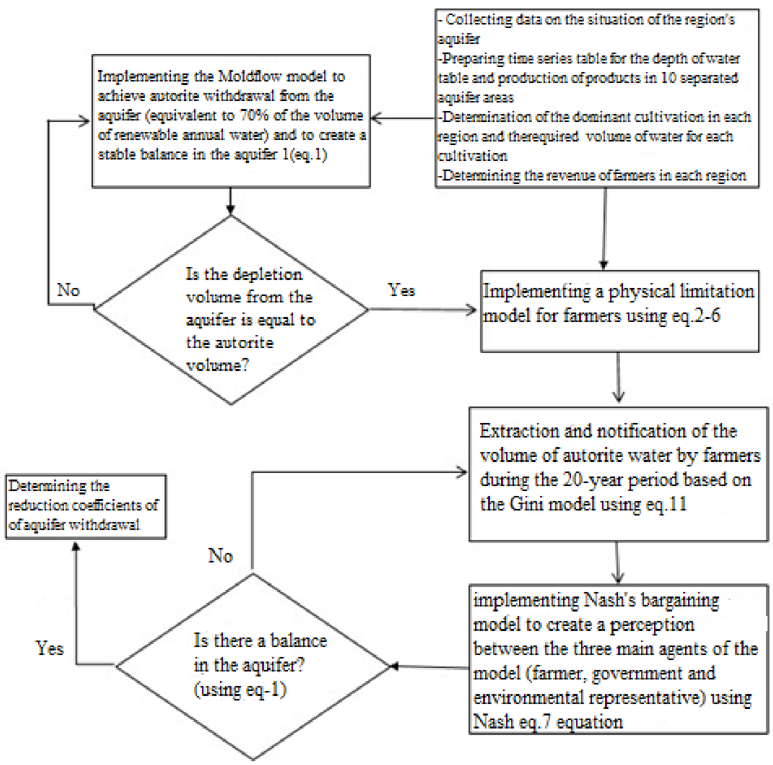


Figure 4: Stages of developing the ABM

4. Results and Discussion

In Table 3, 5 scenarios were observed, aiming at preventing unauthorized exploitation, increasing irrigation efficiency, receiving water price and overdraw fines, increasing the purchase price of products, and reducing the depletion of unauthorized wells. The output of the ABM for each of the above scenarios was presented in Figure 5.

Annual reservoir deficit and cumulative reservoir deficit of Qazvin plain were equal to 160 billion m^3 and 8663 billion m^3, respectively. The objective of implementing these scenarios was to

Table 3: Management scenarios to consider in the developed model

	Scenario				
	1	2	3	4	5
Preventing unauthorized exploitation	✓	—	✓	✓	✓
Increasing irrigation efficiency	✓	✓	—	✓	✓
Receiving water price and overdraw penalty	—	✓	—	✓	✓
Increasing the purchase price of products	—	✓	—	✓	✓
Reducing the depletion of autorite wells	—	—	✓	—	✓

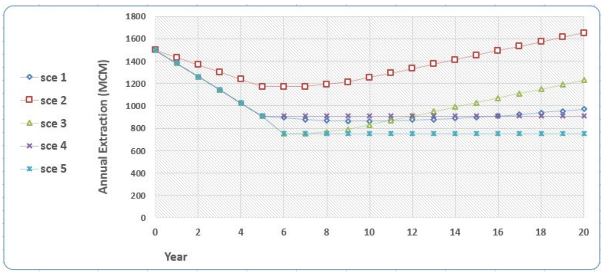


Figure 5: Output parameters variations: Total annual extraction in different scenarios

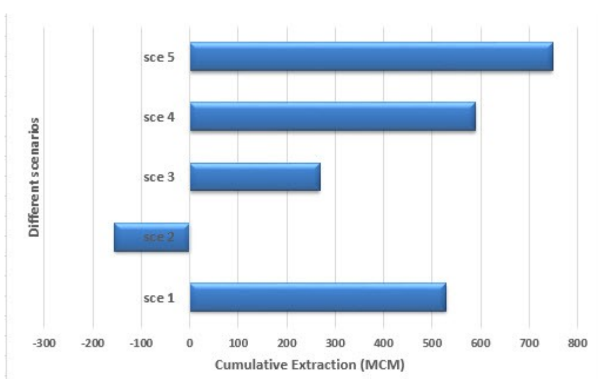


Figure 6: Total cumulative extraction; in different scenarios

drop the annual reservoir deficit to zero in the short term (maximum 5 years) and to compensate for the cumulative reservoir deficit in the long term (20 years). It was attempted in all scenarios to prevent the unauthorized withdrawal in the first five years, to make the aquifer balancing process more meaningful. As observed in Figure 5, the deficit of wells depletion was reduced during the first 5 years by 514 billion m^3 after implementing scenario 1.

This was due to the filling the unauthorized wells and the prevention of overdraw of authorize wells. Then, due to the implementation of pressurized irrigation, the efficiency of irrigation would be enhanced. Still, the depletion volume would be constant due to the development of the area under cultivation. On the other hand, due to the reopening of some unauthorized wells and boring of new unauthorized well, groundwater depletion would increase again. Through interaction strategy and non-prevention of unauthorized withdrawals, which had many social consequences and caused farmers and their families to protest, scenario 2 tended to manage withdrawal of wells by increasing the irrigation efficiency and guaranteed purchase price, but this measure was not hopeful. In the beginning, although it had a slight decrease in the withdrawal, it was continued and resulted in overdraw.

In Scenario 3, at first unauthorized withdrawals were removed, and then, if they did not reach the balancing point, the volume required to comply with the withdrawal limit was decreased from the authorize wells. In this scenario, the depletion of wells was reduced about 549 billion m^3 about 5 years after the start of the plan, but then this value was minimized to 159 billion m^3 to reach the authorize depletion. In this scenario, although the aim of the plan could be met and the deletion of wells could be dropped to the permissible level, it would give rise to unbearable pressure on farmers and caused a lot of resistance. In scenario 4, all measures were observed except for mitigating the withdrawal of authorize wells. In this scenario, there would never be a balance due to unauthorized depletion but would entail relative satisfaction of the exploiters. In Scenario 5, all measures were performed simultaneously. In this scenario, despite the elimination of unauthorized withdrawals to achieve balance, some of the authorize withdrawals were diminished. Still, a portion of farmers' losses was compensated by increasing irrigation efficiency and the purchase price of the products.

Figure 6 displayed the total saved volume by implementing each scenario. Maximum savings were observed in the implementation of scenario

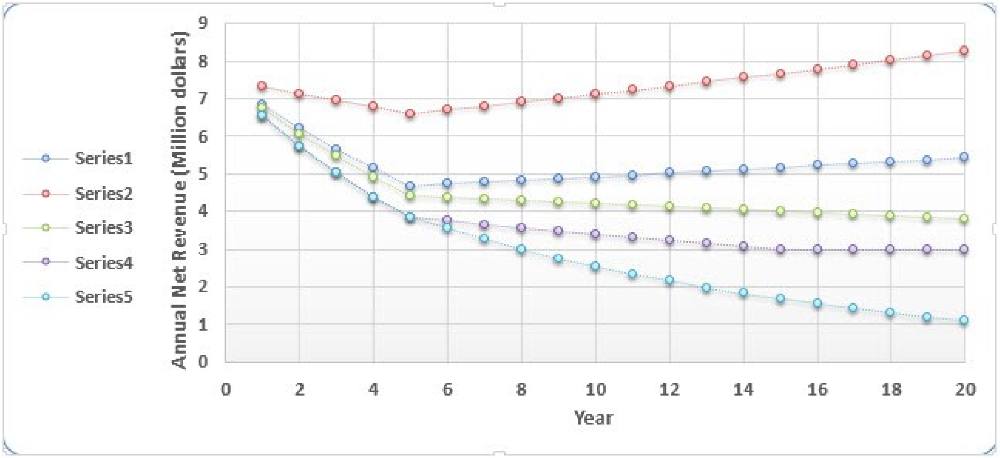
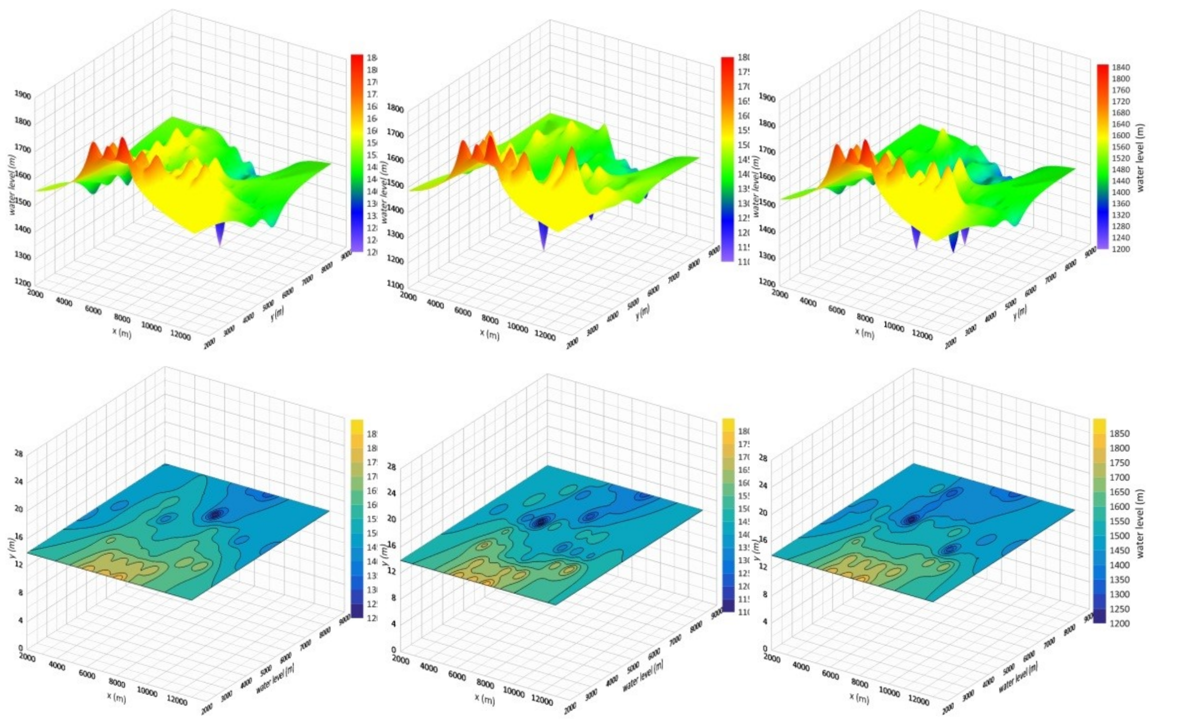


Figure 7: Output total annual net revenue variations in different scenarios



(a) (b) (c)

Figure 8: Changes in the iso-piez map of the study area in two and three-dimensional forms. Images from a to c indicated the effect of reduced groundwater depletion on the region's iso-piez map

5, and an increase in the withdrawal volume from the aquifer was a result of scenario 2.

The output of Figure 7 exhibited that the farmers' revenue reduced due to the implementation of scenarios 3, 4 and 5 in proportion to the volume of withdrawal mitigation from the aquifer. After the implementation of scenario 1, farmers' incomes reduced as the unauthorized withdrawal was prevented for 5 years. But, their revenue increased again due to an increase in irrigation efficiency and the development of the area under cultivation. With respect to non-prevented unauthorized withdrawal in scenario 2, it was observed that the farmers' revenue was slightly minimized due to imposing fines for unauthorized withdrawal and increasing water price during the first few years. However, their revenue was next increased due to an increase in efficiency and also an increase in the guaranteed purchase price.

To review the impact of the implementation of scenarios on groundwater status, it was studied and compared again 5, 10, and 20 years after implementing the plan in different scenarios. Figure 8 indicated that the height of the water table was increased, and the deficit of the aquifer reservoir was compensated by implementing the best scenarios from a to c.

5. Conclusion

This paper utilized ABM as a method to survey the effective solutions for resolving the groundwater crisis in the Qazvin plain. According to the intended strategies and implemented scenarios, it was tried to prevent an overdraw of authorize wells, which was conducted by installing a smart volumetric meter. This prevention was the most noticeable and effective project in controlling the extraction of groundwater resources. Regarding that there were three important and basic factors in the implementation of this project such as the government (ministry of energy and the ministry of agriculture) and the people (farmers) and the environment and the physical and hydrogeological conditions of the region affected by their performance, the ABM was an efficient and practical method for problem-solving and selecting the best scenario for removing existing challenges and performing a project.

The filling unauthorized wells was significantly emerged in reducing aquifers withdrawal. However, since these two measures would reduce farmers' revenue, a lot of resistance would be created against their takings. Hence, it was required to be conductive in compensating the reduced revenue of farmers by applying the compensatory methods such as increasing irrigation efficiency and implementing new irrigation methods and also increasing the guaranteed purchase price. On the interviews with farmers and government representatives and the prepared questionnaires for this purpose, and the obtained results from the implementation of the model, it was inferred that presenting all-inclusive cooperation was suggested to achieve the goals of the plan and reduce withdrawals from the region's aquifers and consequently reach the balanced aquifer.

The interests of all agents should be clear in the measures, and then unilateral actions would not be satisfactory. Since the farmers were affected by each other, it was so vital to creating conditions in which farmers competed positively for maintaining the aquifer of the plain and stop attempting in more exploitation and achieving an optimum result. In the following, it was recommended to study the effectiveness of other methods on the improvements of the condition of the aquifer such as artificial recharge and watershed management by making use of ABM approach, and then to take action based on results in decision-making on the manner of implementation of each project in different study areas of the country.

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