Evaluation of Strategies for Pumping Optimization of Coastal Aquifers Using Numerical Simulation and Game Theory

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Evaluation of Strategies for Pumping Optimization of Coastal Aquifers using Numerical Simulation and Game Theory

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Abstract

In this study, after simulating five years of saltwater intrusion with SEAWAT package in Astaneh-Kouchesfahan coastal aquifer, Iran, 19 strategies, including managerial, structural, and combined strategies, were investigated to reduce the saltwater intrusion. Since managerial solutions cause users' dissatisfaction and structural solutions increase the costs, two-player game theory was used to identify the most appropriate solution. According to the results obtained from game theory, the two strategies of artificial recharge and underground dam had the greatest impact on preventing the saltwater intrusion with the highest satisfaction of stakeholders, so that they decreased the saltwater intrusion from 740 m by 150 and 300 m, respectively, after five years. Therefore, the combined simulator-optimizer method presented in this study can evaluate various solutions, and the most appropriate solution can be proposed with the lowest cost and maximum satisfaction for the sustainable management of coastal aquifers.

Keywords: Costal aquifer, Seawater intrusion, Groundwater management, Numerical simulation, Optimization.

1. Introduction

Today, seawater intrusion into aquifers has become a common phenomenon globally, especially in arid and semi-arid coastal areas due to relatively low precipitation, population growth, and consequently increased groundwater consumption (Petalas et al., 2009; Christelis and Mantoglou, 2019; Javadi et al., 2020). In recent years, in many coastal areas, excessive exploitation of aquifers has undesirably affected the balance of many of them (Werner et al., 2013). Even the results of some studies show that due to the complex geological connections, this over-exploitation of groundwater near the coasts or even far from them can lead to saltwater intrusion from the exploitation wells into the aquifer (Knight et al., 2018; Yu and Micheal, 2019a). On the other hand, rising sea levels due to global warming have further caused the instability and salinization of aquifers (White et al., 2005; Woodworth et al., 2009; Sanford and Pope, 2010). Under these conditions, even pumping saline groundwater to desalinate the aquifer not only does not solve the problem but also causes a freshwater-saltwater interface to move towards the aquifer (Stein et al., 2019). Therefore, it is necessary to determine the optimal pumping rate, especially in coastal areas, to conserve the strategic freshwater resources of coastal aquifers using a combination of simulation models and optimization techniques. On the other hand, rehabilitation of saline aquifers by biological, chemical, and physical techniques is very cost- and time-consuming, and sometimes impossible due to the degree of salinity intrusion (Hussain et al., 2019). In other words, the least costly way to stop or reduce the process of salinity intrusion is to determine the optimal amount of freshwater pumping so that farmers bear the lowest resulting damage.

Since simulation models and optimization techniques alone cannot solve such problems, in many studies, the combination of simulators and optimizers has been used to determine the optimal pumping rate of coastal aquifers (Mantoglou, 2003; Zhou et al., 2003; Uddameri and Kuchanur, 2007; Javadi et al., 2012; Singh, 2014; Malmir et al., 2021).

Research on numerical models to simulate the interface limit and saltwater intrusion rate has increased over the past two decades. In these studies, in the first stage, the groundwater flow model is simulated, and in the next stage, the intrusion of saltwater is simulated by coupling the groundwater flow model to the salinity transfer model (Park & Aral, 2004; Narayan et al., 2007). Numerical models are highly effective in simulating saltwater intrusion, especially when the transition zone is very thick (Llopis-Albert & Pulido-Velazquez, 2014). In these models, in addition to simulating saltwater intrusion, scenarios such as reduced exploitation from pumping wells, climate change, and structural measures have been implemented to improve aquifer conditions (Luyun et al., 2011; Lu et al., 2013; Sherif et al., 2013; Qu et al., 2014; Filippis et al., 2016; Abdoulhalik and Ahmed, 2017; Yu and Micheal, 2019b; Tang et al., 2020).

Despite the widespread use of numerical models in simulating saltwater intrusion as well as various scenarios to reduce this intrusion, the issues related to saltwater intrusion management are still a problem for coastal aquifers. The most important limitation of the above-mentioned studies, which only rely on simulation, is facing many simulation scenarios and the lack of a managerial decision based on technical, economic, and social issues. Therefore, it seems essential to manage the saltwater intrusion into coastal aquifers by combining a large number of simulations by numerical models and identifying the most appropriate decision from the simulation scenarios by optimizing models (Singh, 2014). For example, when it is necessary to use various scenarios of exploitation reduction in exploitation wells (e.g., by 1%, 2%, 3%, etc.), an optimization model should determine the maximum possible exploitation volume from the aquifer to protect the aquifer from the intrusion of saltwater while maximizing the exploitation from wells.

In this regard, according to the type of aquifer's limitations and problems, many studies have been conducted with different objective functions, such as maximizing the exploitation pumping, minimizing the level drop, minimizing the volume of saltwater intrusion into the aquifer, and minimizing the pumping costs (Finney et al., 1992; Hallaji and Yazicigil, 1996; Emch and Yeh, 1998; Das and Datta, 1999; Karterakis et al., 2007; Skiborowski et al., 2012).

According to the literature review, optimal strategies to reduce saltwater infiltration into the aquifer can be divided into conventional methods, physical barriers, and hydraulic barriers (Hussain et al., 2019). Conventional methods are non-structural solutions, including pumping scenarios (Sherif et al., 2013) and relocating wells. Moreover, the optimal methods of the second and third categories, which are mainly structural, include a subsurface barrier, land reclamation, and artificial recharge (Hussain et al., 2019).

Despite many studies on combined simulation-optimization methods to reduce saltwater intrusion into coastal aquifers and introduce an optimal strategy, the research still suffers from two main limitations. The first limitation is that all the proposed strategies are presented regardless of the satisfaction of the stakeholders or farmers of the region. In other words, the proposed strategies are top-down and solid and can cause dissatisfaction among farmers, which will ultimately reduce their success rate. The second limitation is that the economy of the proposed strategies has not been analyzed by optimization models, and they impose a heavy financial burden on the farmer or the government in many cases.

Therefore, in this study, for the first time, the most appropriate scenario or strategy is identified using cooperative game theory (considering government and farmers as the players) based on economic and social indices. To do this, a combination of the simulation model with SEAWAT and game theory optimization model has been used in Astaneh-Kouchesfahan, as one of the coastal aquifers in Iran and the center of tourism and agriculture (rice crop). Finally, the proposed strategies will be investigated by analyzing economic and social indices.

2. Materials and methods

2.1. Methodology

One of the fundamental challenges in coastal aquifers is the reduction of groundwater level due to increased exploitation and the consequent reduction of the hydraulic gradient of the flow in part leading to the sea. The result is the saltwater intrusion with greater density from the bottom of the aquifer to its center. This phenomenon gradually causes land reclamation and degradation of the quality of exploitation wells in these areas, and its continuation can even destroy essential parts of the aquifer. Therefore, developing appropriate treatment strategies to control this environmental problem requires the participation of all stakeholders using a cooperative game model. Figure 1 depicts the flowchart of this research. In the first step, after collecting statistics and information of the region, the quantitative and qualitative status of the aquifer was simulated using the MODFLOW and MT3D codes, respectively, in the GMS software environment. In the next step, using the SEAWAT numerical model, saltwater intrusion in the aquifer outlet was determined in three dimensions. To provide practical strategies, several indices were defined for the parties of a non-cooperative two-player game model. The economic and social satisfactions were considered as the indices of the farmers of the region. Moreover, the improvement of the qualitative conditions of the aquifer and the costs of implementing the strategies for water resources treatment were considered as the indices of the government. These indices were applied based on a weighting method in the game model, and finally, the appropriate strategies to reduce saltwater intrusion were evaluated in achieving the minimum cost and the highest level of social satisfaction.

Figure 1. Research flowchart

2.2. Study area

The southern region of the Caspian Sea in Iran has had the most significant potential in the agricultural sector and the tourism industry of this country. However, in recent years, due to excessive and unstable development, it has faced a remarkable increase in the exploitation of its groundwater resources. The Astaneh-Kouchesfahan aquifer (48°48'- 50°25' N, 37°0'-39°50') is located in a humid climate with an average precipitation of 1500 mm. Most of the groundwater and surface water resources in this area are utilized in agriculture, and more specifically, rice cultivation. With an area of 1300 km^2, it is an alluvial aquifer that is confined in the southwestern parts. This aquifer extends from Sefidroud alluvial fan to the sea, and except for the younger alluviums, which are located in the surface part of the alluvial fan, the alternation of fine-coarse grained elements or all fine-grained elements are seen in other parts of the plain. On the other hand, heavy precipitation in this area, which even reaches 1600 mm in some places, is an essential factor in aquifer recharge. However, in most parts of the Astaneh plain, despite the high volume of alluvial areas, groundwater exploitation is not easy due to the presence of fine-grained deposits.

The geological formations that outcrop from Precambrian to Quaternary include various rocks and deposits such as limestone, shale, sandstone, conglomerate, and inner and outer igneous rocks, as well as various types of destructive deposits such as sand, gravel, and coastal deposits (Figure 2). The Astaneh-Kouchesfahan aquifer is not structurally integrated and includes changes according to the geological structure and stratification. According to geophysical studies conducted in the region, the minimum and maximum alluvial thicknesses are 100 and 250 m, respectively. The bedrock of the plain is a lake deposit, the thickness of which reaches up to 1000 m according to the available information. During exploratory studies, including drilling eight exploratory wells, the transmissivity in this plain is estimated between 100 to 6000 m^2/day, and the average storage coefficient is 2%. The water level in this plain generally varies between 1 to 4 m. The water resources balance in this area shows that more than 41 MCM are extracted annually through wells in the region, which has caused a drop in groundwater level in the outlet sections of the aquifer that leads to the sea. This drop in the aquifer in the outlet section has changed the hydraulic gradient and reduced the volume of groundwater outflows. This has caused the saltwater intrusion from the sea to the coastal areas due to the higher density of the seawater in the outlet section.

Figure 2. Study area

2.3. Simulation of saltwater intrusion

In this study, to simulate saltwater intrusion, it was first necessary to simulate groundwater flow using MODFLOW and then simulate concentration changes using MT3D, and finally, simulate saltwater intrusion due to changes in water density. To simulate water flow under the influence of density changes, the SEAWAT model was used to analyze the density changes. According to Eq. (1), the flow is simulated under the influence of density change

$$\frac{\partial}{\partial x}\left[\rho K_x(\frac{\partial h_f}{\partial x}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial x}\right]+\frac{\partial}{\partial y}\left[\rho K_y(\frac{\partial h_f}{\partial y}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial y}\right]+\frac{\partial}{\partial z}\left[\rho K_f(\frac{\partial h_f}{\partial z}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial z}\right] = \rho S_f\frac{\partial h_f}{\partial t}+\theta\frac{\partial \rho}{\partial C}\frac{\partial C}{\partial t}-p_s q_s \quad (1)$$

where x, y, and z are flow directions, K_x, K_y, and K_z are hydraulic conductivity in flow directions (LT^{-1}), S_f is storage coefficient in the freshwater aquifer (L^{-1}), h_f is equivalent of water level in the freshwater aquifer, θ is effective porosity, ρ is the density of the saltwater, ρ_f is the density of the freshwater, ρ_s is the density of inlet water from a source, q_s is the volumetric velocity rate per unit volume of the aquifer (T^{-1}), C is the concentration of saltwater (LT^{-3}), and t is time.

After simulating the flow and concentration using MODFLOW and MT3D models, the saltwater intrusion simulation from a saltwater resource (such as the sea) to a freshwater resource was performed simultaneously based on hydraulic gradients of the water density changes. This simulation was performed using the SEAWAT model and defining the aquifer outlet boundary in the coastal strip based on changes in concentration and density. Eq. (2) shows the numerical analysis of the simulation due to changes in concentration and density in the coastal aquifer simultaneously

$$\left[1+\frac{\rho_b K_d}{\theta}\right]\frac{\partial(\theta C^k)}{\theta t}=\frac{\partial}{\partial x_i}\left[\theta D_{ij}\frac{\partial c^k}{\partial x_j}\right]-\frac{\partial}{\partial x_i}\left[\theta v_i c^k\right]+q_s c_s^k+\sum R_n \quad (2)$$

where ρ_b is apparent density ($\rho_b=M_s/V_t$), K_d is linear absorption coefficient (distribution coefficient), θ is porosity (dimensionless), c^k is the concentration of solution k, T is time, $x_{i,j}$ is the distance along with the Cartesian coordinates, D_{ij} is the tensor of hydrodynamic diffusion coefficient, v_i is water velocity in a porous medium or Darcy flow velocity, q_s is the volumetric velocity rate per unit volume of the aquifer, and $\sum R_n$, is the unit of the chemical reaction.

According to Eq. (2) and figure 3, several variables, such as saltwater density, freshwater density in the coastal strip, hydraulic conductivity in the coastal strip, chloride (Cl^-) concentration, and the slope of concentration change gradient, were required to simulate the interface limit of saltwater and freshwater along the length and depth of the coastal strip and the intrusion of saltwater.

Figure 3. A schematic figure shows the conception of the saltwater intrusion approach with density and initial concentration of Chloride (mg/l) conceptual model of the aquifer

2.3.1. Conceptual model

The first step to simulate the saltwater intrusion into the groundwater aquifer was to prepare a conceptual model of the aquifer, including boundary conditions, surface grids, depth and limit of the interface, and its geological structure. Since the SEAWAT model structure considers the nature of saltwater intrusion from the sea in three dimensions, the third dimension in the depth of the aquifer was designed in five layers according to the thickness of the aquifer in the aquifer outlet (coastal strip). Since stratification is essential in high depths, the size of each grid cell was considered 1000 by 1000 m on the surface and 2.5 m in depth. The number of cells and layers considered in the aquifer depth was according to the aquifer thickness in the coastal area. A quantitative model (i.e., MODFLOW) and a qualitative model (i.e., MT3D) of the aquifer were prepared to simulate saltwater intrusion by the SEAWAT package. The period of quantitative and qualitative modeling was considered five years from 2012 to 2017. Modules considered in the MODFLOW code included inlet and outlet groundwater fronts of GHB type, aquifer recharge (from return water and infiltration of precipitation and runoff), and discharge (from exploitation wells). In the next step, the coastal strip (Figure 4) was simulated using MT3D and SEAWAT qualitative models in order to investigate the intrusion of saltwater fronts in the aquifer outlet. Advection and dispersion processes were used to simulate the transfer of solutes during the simulation with the MT3D model. For qualitative simulation according to the intrusion of saltwater, the chloride (Cl^-) was selected as a qualitative variable. After determining the boundary conditions in quantitative modeling, the boundary conditions of the qualitative conceptual model of the aquifer were defined based on the fronts of chloride concentration entering the aquifer. According to Figure 4, three inlet fronts, including the aquifer surface (recharge from the return water, I_1), the concentration of saltwater entering from the coastal strip (GHB boundary layer at the end of the aquifer, I_2), and the concentration entering from the inlet boundary of groundwater flow (GHB boundary layer at the beginning of aquifer, I_3), were considered in the qualitative conceptual model.

After qualitative simulation using the MT3D model and determining the changes in chloride concentration and how it enters the aquifer, the SEAWAT model was used to determine the amount of intrusion into the aquifer as a measure of freshwater and saltwater interface limit. In this model, the boundary of saltwater fronts versus the boundary of freshwater fronts was defined as GHB based on the MT3D model's results. The VDF package was used In the SEAWAT model to determine the initial concentration of chloride in the aquifer (freshwater) and the concentration of chloride in saltwater, as well as the density of saltwater and freshwater. According to the available information, the average density of saltwater in the outlet of the aquifer is 1025 kg/m^3, while the salt concentration is 33 kg/m^3. Therefore, the change in density/concentration slope, which is introduced as DRHODC, was obtained using Eq. (3).

$$\mathrm{Density/consentration\,.\,slop(DRHODG)}: \frac{1025(\mathrm{kg/m}\ ) - 1000(\mathrm{kg/m3}\ )}{33(\mathrm{kg/m3}\ ) - 0(\mathrm{kg/m3}\ )} = 0.75 \qquad (3)$$

Similar to the MODFLOW quantitative and MT3D qualitative models, the simulation period was considered three years to determine the advancement of saltwater.

Figure 4. Study area and the conceptual model of the aquifer

2.4. Developing a conflict resolution model

One of the essential aspects of groundwater resources management is decision making and providing solutions with a view to sustainable development. In other words, water supply and maintaining the quantity and quality of the aquifer at the lowest cost and the highest level of social satisfaction is one of the most important goals of groundwater resources management (Thomann et al., 2020). On the other hand, these goals are feasible when all stakeholders and government are involved in the decision-making process. Of course, this makes the decision-making conditions very difficult due to the multiplicity of decision-makers and their views and even causes conflicts. Therefore, in such circumstances, all the desirability, disagreements, and relative power of decision-makers should be considered in providing the final solution. There are several methods to develop conflict resolution models. The Nash conflict resolution theory is one of the methods of game theory that involves disagreements and the risk of the presence of the participants or players. Nash proves that if H is a convex, closed, and finite function, there will be only one solution ($\varphi(H,d)$) for the conflict resolution, which is obtained by solving the optimization problem of Eq. (4)

$$\begin{aligned} &Maximize: \prod_{i=1}^{N}(f_i - d_i)^{c_i} \qquad ; \; c_i > 0 \\ &s.t: \qquad d_i \le f_i \le \overline{f}_i \; (i = 1,2,\dots,N) \\ &(f_1,\dots,f_n) \in H \end{aligned} \tag{4}$$

Where $\overline{f}_i$ is the maximum desirability that can be involved with the player i, and c_1, c_2, …, c_i represent the relative weight of the stakeholders and the relative power of the decision-makers. In the case of implementing a cooperative game between the parties, all these coefficients will be equal to 1. In contrast, in non-cooperative game models and having relative power, these coefficients will have different values, and their sum equals 1.

One of the essential parts of game model development is defining indices for evaluations and final decision-making. These indices are defined based on the goals and desires of the game parties. As a party to the game, the stakeholders of the region generally use the exploited groundwater resources for agricultural purposes. If the groundwater exploitation is reduced by the other side of the game, the farmers' economy will face critical problems, and social conflicts such as unemployment or rebellion will occur. Therefore, the most important index to assess the evaluation of the farmer as a player in the game model is socio-economic satisfaction. On the other hand, over-exploitation reduces the groundwater level in the aquifer and decreases the quality of the aquifer due to saltwater intrusion. Therefore, to balance the aquifer, an index can be considered for the governmental custodians of water supply as the player of the other side of the game: improving the qualitative condition of the aquifer. Moreover, as the custodian of the water supply, the government should spend money to maintain the sustainable use of the aquifer. Therefore, an economic index can also be considered as an index of the cost of aquifer sustainability for the government. Therefore, in total, an index (socio-economic satisfaction) for the stakeholders in the region and two indices (improving the qualitative status of the aquifer and the cost of aquifer sustainability) for the government were defined in this study.

2.4.1. Socio-economic satisfaction.

Satisfaction is a concept derived from economic development, and this development occurs when poverty and its symptoms are removed from society. This is seen when the fair distribution of resources is conducted to increase the welfare of society (Keane et al., 2008). To define an index for measuring satisfaction, the real stakeholders should first be identified, and their satisfaction should then be evaluated. The social satisfaction index defines as stakeholders' participation in groundwater management, education and information, law, equitable allocation, and social justice. The PI combined index is used to develop an appropriate socio-economic index in evaluating coastal aquifer treatment strategies (Castilla-Rho et al., 2019). This index is a combination of three scores: economic, institutional, and social. The economic score is directly proportional to the gross margin of crop production and includes costs related to the area under cultivation and pumping. The institutional score is defined as the percentage of satisfaction (0-100%) in implementing treatment strategies. Social score involves evaluating the rate of exit from the project by the stakeholders. This score measures the degree of non-cooperation with the governmental custodians to implement the treatment strategies (non-acceptance of the rules). Accordingly, this index is defined as Eq. (5) (Castilla-Rho et al., 2019).

$$PI = E \times I \times S \tag{5}$$

2.4.2. Aquifer qualitative sustainability.

Since the aquifer outlet in the coastal area is affected by the influence of saline seawater, the aquifer qualitative sustainability index was used to assess the aquifer quality. This index is based on the length of the saltwater intrusion (Eq. 6)

$$\alpha_L = 100 \times \left(\frac{L_{Int} - L_{qs}}{L_{Int}}\right) \tag{6}$$

Where L_{qs} is the length of saltwater intrusion after applying the scenario (m/km), L_{Int} is the length of saltwater intrusion in the initial conditions (without applying the scenario) (m/km), and α_L is the qualitative sustainability index (%). The range of changes of this index is between +1 to -∞. The closer the value of this index is to +1, the better the aquifer quality in terms of saltwater intrusion and causes saltwater recession. The intrusion of saltwater reduces this index, and the intrusion length in the initial conditions and after applying the scenarios is obtained based on the simulation results of the SEAWAT model.

2.4.3. Aquifer sustainability cost.

Implementing various scenarios to improve the poor quality of the aquifer in a region by the government requires costs. On the other hand, the amount of money spent along with the participation and satisfaction of farmers will achieve maximum efficiency. In order to estimate this index, the costs of implementing the scenarios for the aquifer sustainability were estimated and normalized using Eq. (7) to be applied in economic calculations

$$C = \frac{C_{max} - C_i}{C_{max}} \tag{7}$$

Where C_{max} is the maximum cost of implementing the scenarios and C_i is the cost of each scenario. C has a value between 0 (for a solution with the highest implementation cost) and 1 (for a solution with the lowest implementation cost).

2.5. Scenarios

In this study, to reduce saltwater intrusion, scenarios with managerial and structural objectives were developed. The managerial scenario was more focused on the aquifer outlet and included exploitation reduction from wells in the area. Moreover, the structural scenario included artificial recharge and constructing an underground dam. Besides, to further improve the quantitative and qualitative condition of the aquifer, combinations of these scenarios were also considered. Based on this, 19 strategies were considered in this study to improve the aquifer condition (Table 1). According to the table, exploitation reduction was considered at four levels of 5, 10, 15, and 20%.

3. Results and discussion

3.1. Simulation results of saltwater intrusion

In this study, the saltwater intrusion was simulated using SEAWAT numerical model. After the calibration of the model in quantitative mode by MODFLOW to simulate the flow, the solute transfer model of MT3DMs was performed based on chloride concentration changes for qualitative simulation. Calibration in the qualitative model was performed by trial and error method, and longitudinal dispersion was analyzed and calibrated. Due to the lack of data related to the pollution transfer, the calibration of the longitudinal dispersion coefficient was performed using the hydraulic conductivity, the type of geological formations in the area, the slope of the aquifer outlet, land use, and qualitative samplings. Figure 5 depicts the changes in chloride concentration in the aquifer at the end of the simulation period. The results of a 5-year simulation period in the aquifer outlet showed that the chloride concentration in the western part increased more than in other parts. The western part of the aquifer has been affected by the intrusion of seawater up to a distance of more than 1 km, and the chloride concentration has reached more than 280 mg/l. The study of groundwater exploitation networks shows that the volume of exploitation of groundwater resources in the western part is higher than that in the eastern part. This is the most crucial reason for the increase of saltwater intrusion in western parts. On the other hand, the eastern part of the aquifer is affected by surface water flows. The Sefidroud river is the largest source of surface water in this region, so the rate of increase in chloride concentration is lower than that in the western part.

Figure 5. Simulation of the MT3DMs model in the aquifer outlet section

After simulating the chloride concentration changes in the aquifer using the MT3DMs model, the saltwater intrusion was performed using the SEAWAT model. In this model, by introducing the parameters of the VDF package in the model, the initial concentration of chloride in the aquifer, the concentration of salt in the saltwater, and the density of saltwater and freshwater were considered as the initial and boundary conditions. Figure 6 depicts the simulation results at the aquifer depth and saltwater intrusion into the deep layers. The simulation results in the aquifer depth showed that saltwater intrusion was 740 m during the 5-years study period from 2012 to 2017. This intrusion is mostly due to groundwater exploitation and hydraulic gradient reduction.

Figure 6. Three-dimensional view of SEAWAT model in the aquifer outlet

3.2. Evaluating the indices of the conflict resolution model

In the proposed game model, three indices of aquifer qualitative sustainability, aquifer sustainability cost, and socio-economic satisfaction of stakeholders in the region were considered. Stakeholders in the region include farmers in the aquifer outlet who use the exploited water. The other side is the water sector managers as the representatives of the government, which involve the two indices of aquifer qualitative sustainability and aquifer sustainability cost in the conflict resolution model.

After applying the treatment strategies in the SEAWAT model, the saltwater intrusion and the aquifer qualitative sustainability index were calculated using Eq. (6). Each treatment strategy was economically analyzed, and based on this, the cost of implementing the solutions was calculated. The highest implementation cost belonged to the construction of the underground dam, while the lowest cost was related to the aquifer exploitation reduction. After the normalization of economic values, the aquifer sustainability cost was calculated (Table 1). A total of 40 questionnaires was distributed among the farmers in the west, east, and center of the region to estimate the socio-economic satisfaction index in the region. The number and method of completing the questionnaires were determined using the Delphi method. Socio-economic satisfaction was assigned a score between 0 and 1 with a Likert scale for each strategy. A score of 0 indicated dissatisfaction, and a score of 1 indicated the maximum level of satisfaction.

Due to the non-cooperative game approach for the conflict resolution model, each side of the game should be determined by one index. Therefore, for the government player in this study, the two indices of aquifer qualitative sustainability and aquifer sustainability cost were combined by weighting using analytic hierarchy process (AHP), the resulting index was then called the government index (Table 1). In order to weigh by AHP, 30 questionnaires were distributed among and water experts and managers in the region. Based on the results, the weights of the aquifer qualitative sustainability and sustainability cost indices were obtained to be 0.6 and 0.4, respectively.

Table 1 shows that by increasing the amount of aquifer qualitative sustainability, social satisfaction decreases sharply. Increasing the aquifer quality index has a direct relationship with decreasing water exploitation or increasing aquifer recharge. Therefore, due to the important role of agriculture in their livelihood, farmers strongly opposed reducing the level of water exploitation.

Table 1. Indices of conflict resolution parties in the game model

3.3. Determining the optimal minimum (F^*)

Given the game model approach using the asymmetric Nash equation in this study, determining the optimal minimum for each index and each player is essential. The concept of optimal minimum in the Nash equation indicates the entry of a strategy into the game model. Strategies in which the index value of each player is less than the optimal minimum do not enter the game model. Determining the optimal minimum was conducted based on the purpose of this study and the comments from experts. According to the condition of the Astaneh-Kouchesfahan aquifer and the importance of saltwater intrusion, the optimal minimum for the qualitative sustainability index was considered to be 0.5. This value means a 370-m recession of the saltwater. The minimum aquifer sustainability cost was considered zero due to the importance of lowering the costs by the government. This means that the maximum cost to recover the aquifer is borne by the governmental management of water resources. Therefore, according to the weight of 0.6 and 0.4 considered for the two indices of qualitative sustainability and sustainability cost, the optimal minimum for the government index was calculated to be 0.3. To determine the optimal minimum for socio-economic satisfaction based on the decision-making in a democratic environment, 50% was considered for the optimal minimum of this index.

3.4. Prioritizing the selected strategies

After calculating the indices of the two parties of the game, the final value of the game model index for each player was calculated based on the asymmetric Nash equation. Based on the results, only 12 treatment strategies were entered the game model, and the rest, which had index values less than the optimal minimum, omitted. The strategies that entered the game model were prioritized based on the maximum Nash index. Table 2 shows the prioritization of the best five strategies along with their calculated Nash index values. According to the table 2, despite of decreasing in the high rate of saltwater intrusion in the fourth priority (410 meter) compared to the continuation of the business as usual (740 meter), but taking into account social, economic indicators and finally the output of game theory the artificial recharge in the aquifer outlet section has been selected as the first priority agreed between the parties to the game. The technical analysis of this strategy in the SEAWAT model shows that the control of saltwater intrusion and a water recession equal to 150 m occurred during a 5-year simulation period. After this strategy, in terms of increasing the qualitative sustainability index of the aquifer, the combined strategy of constructing the underground dam and artificial recharge resulted in a qualitative sustainability index of 0.55 and a 410 m recession of saltwater in the aquifer outlet. Figure 7 shows the simulation results of the first and second priority strategies for the aquifer qualitative sustainability index. Table 2 indicates that all the selected strategies had socio-economic satisfaction indices higher than 70%. Therefore, sensitivity analysis of the indices of this game model was necessary to analyze the results.

Table 2. Prioritization of the selected strategies

Figure 7. Results of saltwater intrusion by SEAWAT model from the sea for the all strategies: a) Business as usual b) Artificial recharge c) Underground dam d) 5% Exploitation reduction e) Underground dam + Artificial recharge f) 5% Exploitation reduction + artificial recharge

3.5. Sensitivity analysis of the game model

Given the results obtained from the prioritization of treatment strategies, a sensitivity analysis of the game model indices was necessary. According to the use of the asymmetric Nash model, the sensitivity of the two weights of the government player indices and relative power coefficient (α) of players were analyzed. The values of the two indices of aquifer qualitative sustainability and aquifer sustainability cost varied between 0.2 and 0.8 for sensitivity analysis (Figure 8). The results showed that by increasing the weight of the aquifer qualitative sustainability index, the combined strategy of artificial recharge and construction of the underground dam was the first priority. This strategy had the maximum socio-economic satisfaction with high qualitative sustainability. By reducing the weight of the aquifer qualitative sustainability index, artificial recharge was selected as the strategy with high priority. This strategy also provided maximum socio-economic satisfaction.

Figure 8. Sensitivity analysis of the weight of qualitative sustainability and sustainability cost indices

The second technique to analyze the sensitivity of the game model is to change the relative power between the two players. This coefficient varied between 0.3 and 0.7, and the results were analyzed. By increasing the relative power of the parties to the game, an attempt was made to determine a range for changing the prioritization of treatment strategies. Figure 9 shows the changes in the relative power of the government player due to the various strategies that have entered the game model. The results indicate that by increasing the relative power of the stakeholders, the artificial recharge strategy had more priority. In contrast, the exploitation reduction equal to 5% was chosen as the first priority by increasing the relative power of the government.

Figure 9. The sensitivity analysis of the relative power of the government in the conflict resolution model

4. Conclusion

Using a combination of managerial and structural scenarios, strategies for coastal aquifer management against saltwater intrusion were presented in this study. In the first step, by simulating the saltwater intrusion into the coastal aquifer using the SEAWAT package, it was determined that the saltwater advanced up to 740 m from the coastal area to the aquifer after a 5-year period. Therefore, a set of management strategies was proposed to reduce this environmental damage. In previous studies, several structural strategies were evaluated, some of which, such as surface and subsurface physical barriers, had high construction costs despite their high efficiency (Hussain et al., 2019). In other studies, using non-structural and managerial approaches and using optimization models (Singh, 2014), the optimal pumping was determined to reduce the aquifer exploitation and saltwater intrusion. On the other hand, it has been observed in many studies that the use of non-structural strategies such as reducing aquifer exploitation can result in the dissatisfaction of stakeholders and many social conflicts (Ghafouri et al., 2020). The literature review shows that structural and non-structural strategies can lead to failure in terms of cost imposition and social dissatisfaction. Therefore, in this research, a combined simulator-optimizer, i.e., the SEAWAT-game theory model, was used to prioritize the proposed strategies for each region.

The results obtained for the study area showed that the exploitation from the Astaneh-Kouchesfahan coastal aquifer in northern Iran, despite abundant surface water resources, has led to the advancement and intrusion of saltwater. The results of the SEAWAT package showed that if the exploitation from the aquifer continues in its current form, the saltwater will advance by 740 m in the next five years. This intrusion in the near future will degrade the quality of a significant portion of the aquifer. Therefore, in this study, 19 structural and non-structural strategies were proposed to reduce saltwater intrusion. Since previous studies have shown that structural and non-structural strategies have their own advantages and disadvantages, the selected strategies were prioritized using an optimization model. According to the results of a model based on game theory, out of 19 strategies, five strategies had priority in terms of socio-economic satisfaction. The results of prioritization showed that the two strategies of artificial recharge and underground dam were the most effective solutions in reducing the saltwater intrusion, so that the implementation of these strategies reduces the saltwater intrusion from 740 m by 150 and 300 m, respectively. Therefore, by using the combined simulator-optimizer method presented in this study, various solutions can be evaluated to propose the most appropriate solution with the lowest cost and maximum satisfaction for the sustainable management of coastal aquifers.

References

Abdoulhalik A, Ahmed AA. 2017. The effectiveness of cutoff walls to control saltwater intrusion in multi-layered coastal aquifers: Experimental and numerical study. J. Environ. Manag. 199/:62–73. https://doi.org/10.1016/j.jenvman.2017.05.040

Castilla-Rho JC, Rojas R, Andersen MS, Holley C, Mariethoz G. 2019. Sustainable groundwater management: How long and what will it take?. Global Environmental Change. *58*:101972. https://doi.org/10.1016/j.gloenvcha.2019.101972

Christelis V, Mantoglou A. 2019. Pumping Optimization of Coastal Aquifers Using Seawater Intrusion Models of Variable-Fidelity and Evolutionary Algorithms. Water Resour. Manage. 33:555–568. https://doi.org/10.1007/s11269-018-2116-0

Das A, Datta B. 1999. Development of management models for sustainable use of coastal aquifers. J. Irrig. Drain. Eng. 125:112–121. https://doi.org/10.1061/(ASCE)0733-9437(1999)125:3(112)

Emch PG, Yeh WG. 1998. Management model for conjunctive use of coastal surface water and groundwater. J. Water Resour. Plann. Manage. 1243:129–139. https://doi.org/10.1061/(ASCE)0733-9496(1998)124:3(129)

Filippis DG, Foglia L, Giudici M, Mehl S, Margiotta S, Negri SL. 2016. Seawater intrusion in karstic, coastal aquifers: Current challenges and future scenarios in the Taranto area (southern Italy). Sci. Total Environ. 573:1340–1351. https://doi.org/10.1016/j.scitotenv.2016.07.005

Finney BA, Samsuhadi S, Willis R. 1992. Quasi–three dimensional optimization model of Jakarta basin. J. Water Resour. Plann. Manage. 118:18–31. https://doi.org/10.1061/(ASCE)0733-9496(1992)118:1(18)

Hallaji K, Yazicigil H. 1996. Optimal management of coastal aquifer in Southern Turkey. J. Water Resour. Plann. Manage. 122:233–244. https://doi.org/10.1061/(ASCE)0733-9496(1996)122:4(233)

Hussain MS, Abd-Elhamid HF, Javadi A, Sherif M. 2019. Management of Seawater Intrusion in Coastal Aquifers: A Review. Water. 11, 2467. https://doi.org/10.3390/w11122467

Javadi AA, Abd-Elhamid HF, Farmani R. 2012. A simulation–optimization model to control seawater intrusion in coastal aquifers using abstraction/recharge wells. Int. J. Numer. Anal. Met. 36(16): 1757–1779. https://doi.org/10.1002/nag.1068

Javadi S, Kardan Moghaddam H, Neshat A. 2020. A new approach for vulnerability assessment of coastal aquifers using combined index. Geocarto Int. 29:1-23. https://doi.org/10.1080/10106049.2020.1797185

Karterakis SM, Karatzas GP, Nikolos IK, Papadopoulou MP. 2007. Application of linear programming and differential evolutionary optimization methodologies for the solution of coastal subsurface water management problems subject to environmental criteria. J. Hydrol. 342:270–282. https://doi.org/10.1016/j.jhydrol.2007.05.027

Keane A, Jones JPG, Edwards Jones G, Milner Gulland EJ. 2008. The sleeping policeman: understanding issues of enforcement and compliance in conservation. Anim. Conserv. 11(2):75–82. https://doi.org/10.1111/j.1469-1795.2008.00170.x

Kharanagh SG, Banihabib ME, Javadi S. 2020. An MCDM-based social network analysis of water governance to determine actors' power in water-food-energy nexus. J. Hydrol. 581:124382. https://doi.org/10.1016/j.jhydrol.2019.124382

Knight AC, Werner AD, Morgan LK. 2018. The onshore influence of offshore fresh groundwater. J. Hydrol. 561:724-736. https://doi.org/10.1016/j.jhydrol.2018.03.028

Llopis- Albert C, Pulido- Velazquez D. 2014. Discussion about the validity of sharp-interface models to deal with seawater intrusion in coastal aquifers. Hydrol. Processes 28(10):3642–3654. https://doi.org/10.1002/hyp.9908

Lu CY, Chen C, Zhang J.L. 2013. Steady-state freshwater-seawater mixing zone in stratified coastal aquifers. J. Hydrol., 505:24-34. https://doi.org/10.1016/j.jhydrol.2013.09.017

Luyun R, Momii K. Nakagawa K. 2011. Effects of Recharge Wells and Flow Barriers on Seawater Intrusion. Ground Water 49:239–249. https://doi.org/10.1111/j.1745-6584.2010.00719.x

Malmir M, Javadi S, Moridi A, Neshat A, Razdar B. 2021. A new combined framework for sustainable development using the DPSIR approach and numerical modeling. Geosci. Front. 12(4):101169. https://doi.org/10.1016/j.gsf.2021.101169

Mantoglou A. 2003. Pumping management of coastal aquifers using analytical models of saltwater intrusion. Water Resour. Res. 39(12). https://doi.org/10.1029/2002WR001891

Narayan KA, Schleeberger C, Bristow KL. 2007. Modelling seawater intrusion in the Burdekin Delta irrigation area, North Queensland, Australia. Agric. Water Manage. 89(3):217–228. https://doi.org/10.1016/j.agwat.2007.01.008

Park CH, Aral MM. 2004. Multi-objective optimization of pumping rates and well placement in coastal aquifers. J. Hydrol. 290(1):80–99. https://doi.org/10.1016/j.jhydrol.2003.11.025

Petalas C, Pisinaras V, Gemitzi A, Tsihrintzis VA, Ouzounis K. 2009. Current conditions of saltwater intrusion in the coastal Rhodope aquifer system, northeastern Greece. Desalination. 237:22–41. https://doi.org/10.1016/j.desal.2007.12.020

Qu W, Li H, Wan L, Wang X, Jiang X. 2014. Numerical simulations of steady-state salinity distribution and submarine groundwater discharges in homogeneous anisotropic coastal aquifers. Adv. Water Resour. 74:318-328. https://doi.org/10.1016/j.advwatres.2014.10.009

Qu W, Li H, Wan L, Wang X, Jiang X. 2014. Numerical simulations of steady-state salinity distribution and submarine groundwater discharges in homogeneous anisotropic coastal aquifers. Adv. Water Resour. 74:318–328. https://doi.org/10.1016/j.advwatres.2014.10.009

Sanford WE, Pope JP. 2010. Current challenges using models to forecast seawater intrusion, lessons from the Eastern Shore of Virginia, USA. Hydrogeol. J. 18:73–93. https://doi.org/10.1007/s10040-009-0513-4

Sherif M, Sefelnasr A, Ebraheem AA, Javadi A. 2013. Quantitative and qualitative assessment of seawater intrusion in Wadi Ham under different pumping scenarios. J. Hydrol. Eng. 19(5):855–866. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000907

Singh A. 2014. Managing the environmental problem of seawater intrusion in coastal aquifers through simulation–optimization modeling. Ecol. Indic. 48:498–504. https://doi.org/10.1016/j.ecolind.2014.09.011

Skiborowski M, Mhamdi A, Kraemer K, Marquar W. 2012. Model-based structural optimization of seawater desalination plants. Desalination 292:30–44. https://doi.org/10.1016/j.desal.2012.02.007

Stein S, Yechieli Y, Shalev E, Kasher R, Sivan O. 2019. The effect of pumping saline groundwater for desalination on the fresh–saline water interface dynamics. Water Res. 156: 46–57. https://doi.org/10.1016/j.watres.2019.03.003

Tang G, Yang M, Chen X, Jiang T, Chen T, Chen X, Fang H. 2020. A new idea for predicting and managing seawater intrusion in coastal channels of the Pearl River, China. J. Hydrol. 590:125454. https://doi.org/10.1016/j.jhydrol.2020.125454

Thomann JA, Werner AD, Irvine DJ, Currell MJ. 2020. Adaptive management in groundwater planning and development: a review of theory and applications. J. Hydrol. 586:124871. https://doi.org/10.1016/j.jhydrol.2020.124871

Uddameri V, Kuchanur M. 2007. Simulation–optimization approach to assess groundwater availability in Refugio County. TX. Environ. Geol. 51(6):921–929. https://doi.org/10.1007/s00254-006-0455-2

Werner AD, Bakker M, Post VE, Vandenbohede A, Lu C, Ataie-Ashtiani B, Simmons CT, Barry DA. 2013. Seawater intrusion processes, investigation and management: recent advances and future challenges. Adv. Water Resour. 51:3–26. https://doi.org/10.1016/j.advwatres.2012.03.004

White NJ, Church JA, Gregory JM. 2005. Coastal and global averaged sea level rise for 1950 to 2000. Geophys. Res. Lett. 32:1. https://doi.org/10.1029/2004GL021391

Woodworth PL, White NJ, Jevrejeva S, Holgate SJ, Church JA, Gehrels WR. 2009. Evidence for the accelerations of sea level on multi-decade and century timescales. Int. J. Climatol. 29:777–789. https://doi.org/10.1002/joc.1771

Yu X, Michael HA. 2019a. Mechanisms, configuration typology, and vulnerability of pumping-induced seawater intrusion in heterogeneous aquifers, Adv. Water Resour. 128, 117-128. https://doi.org/10.1016/j.advwatres.2019.04.013

Yu X, Michael HA. 2019b. Offshore pumping impacts onshore groundwater resources and land subsidence. Geophys. Res. Lett. 46:2553–2562. https://doi.org/10.1029/2019GL081910

Zhou X, Chen M, Liang C. 2003. Optimal schemes of groundwater exploitation for prevention of seawater intrusion in the Leizhou Peninsula in Southern China. Environ. Geol. 43:978–985. https://doi.org/10.1007/s00254-002-0722-9

Figures

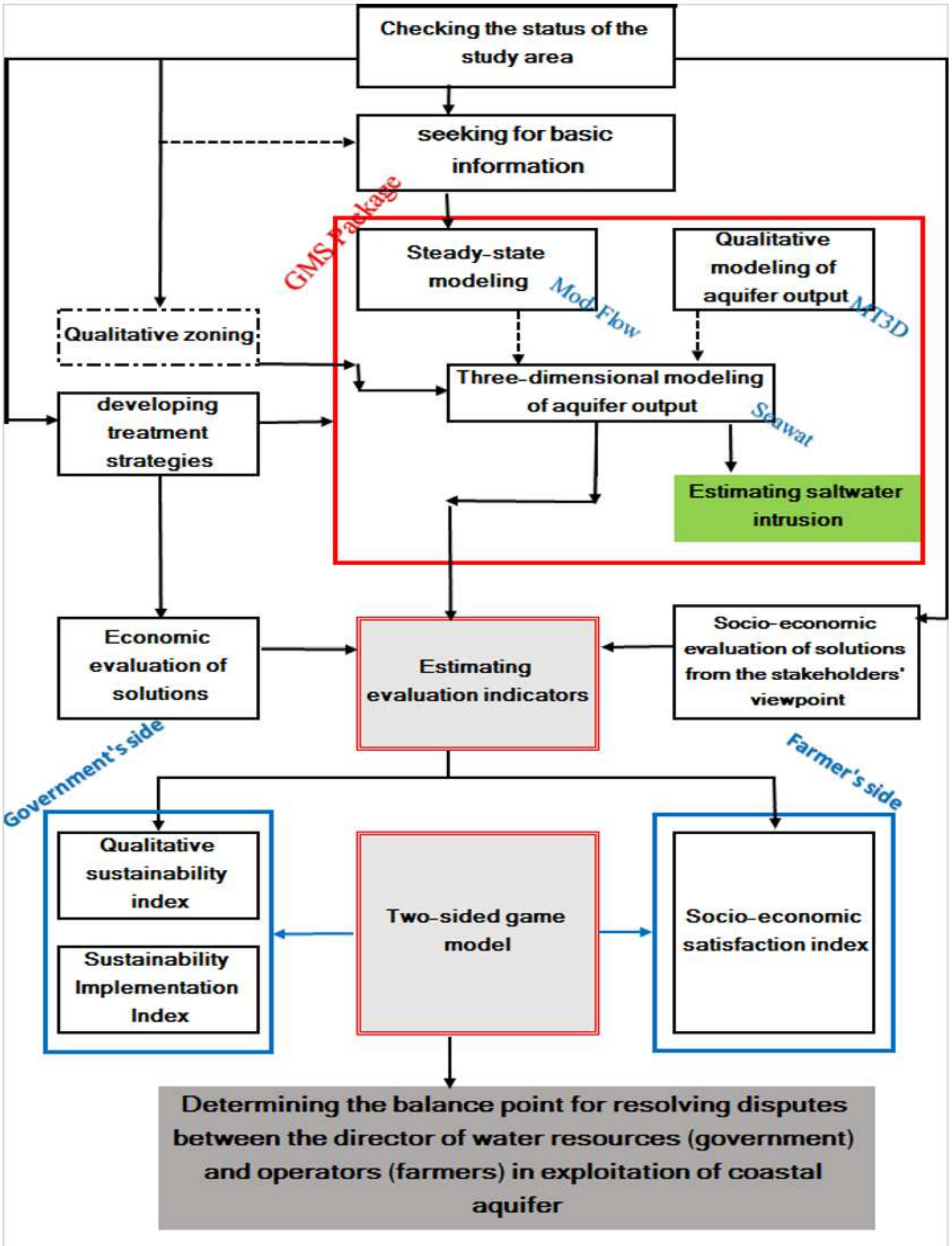


Figure 1

Research flowchart

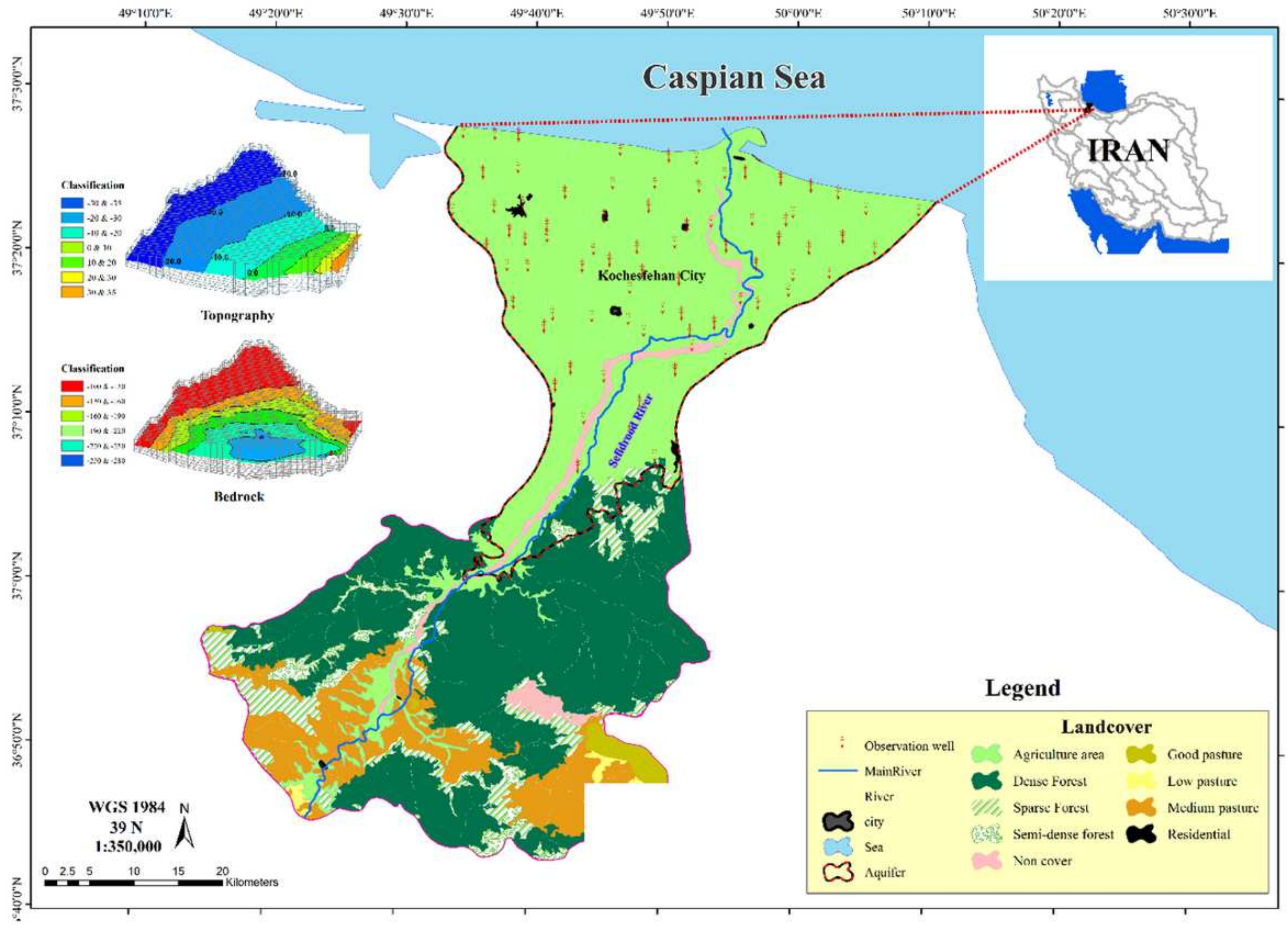


Figure 2

Study area

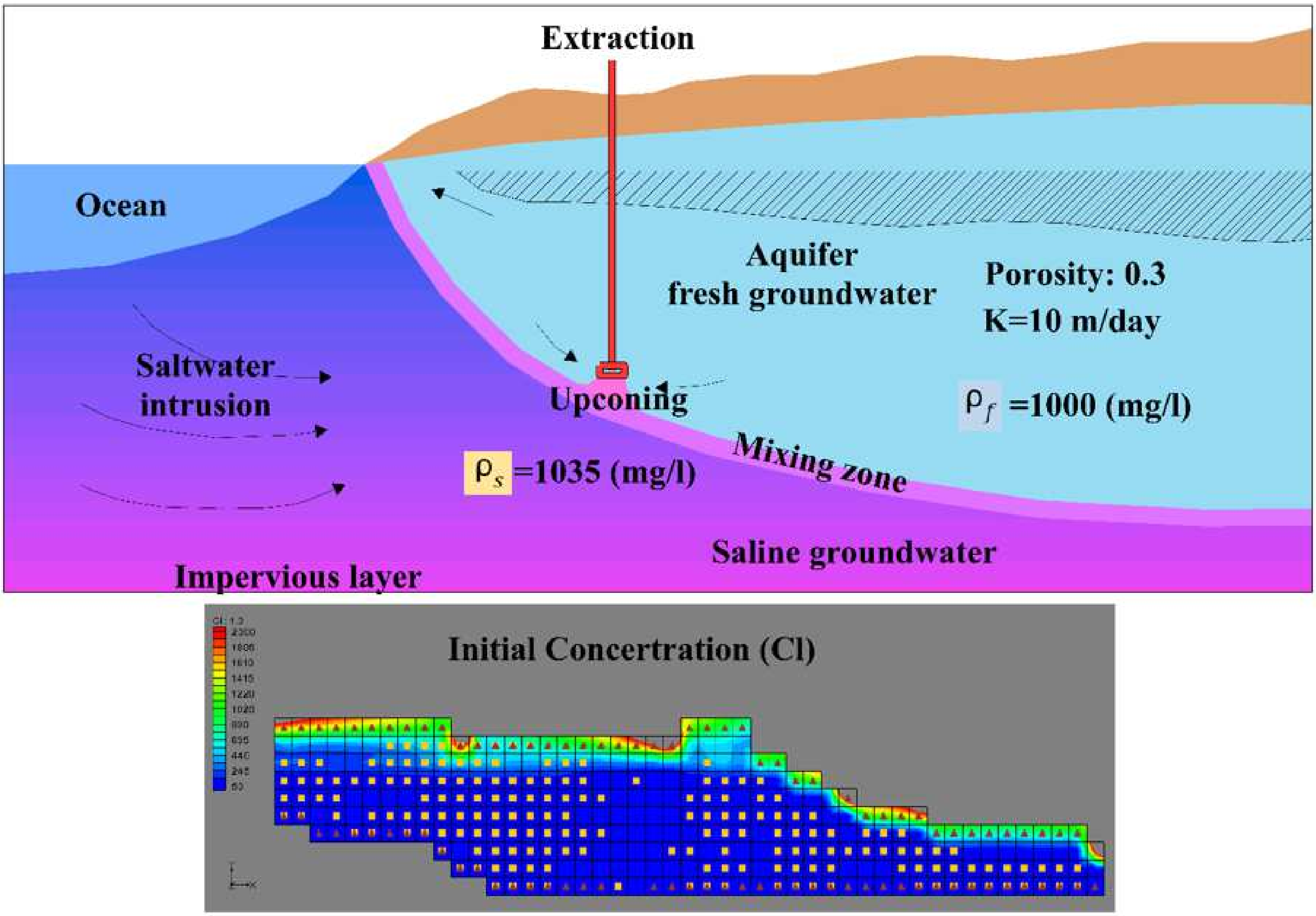


Figure 3

A schematic figure shows the conception of the saltwater intrusion approach with density and initial concentration of Chloride (mg/l) conceptual model of the aquifer

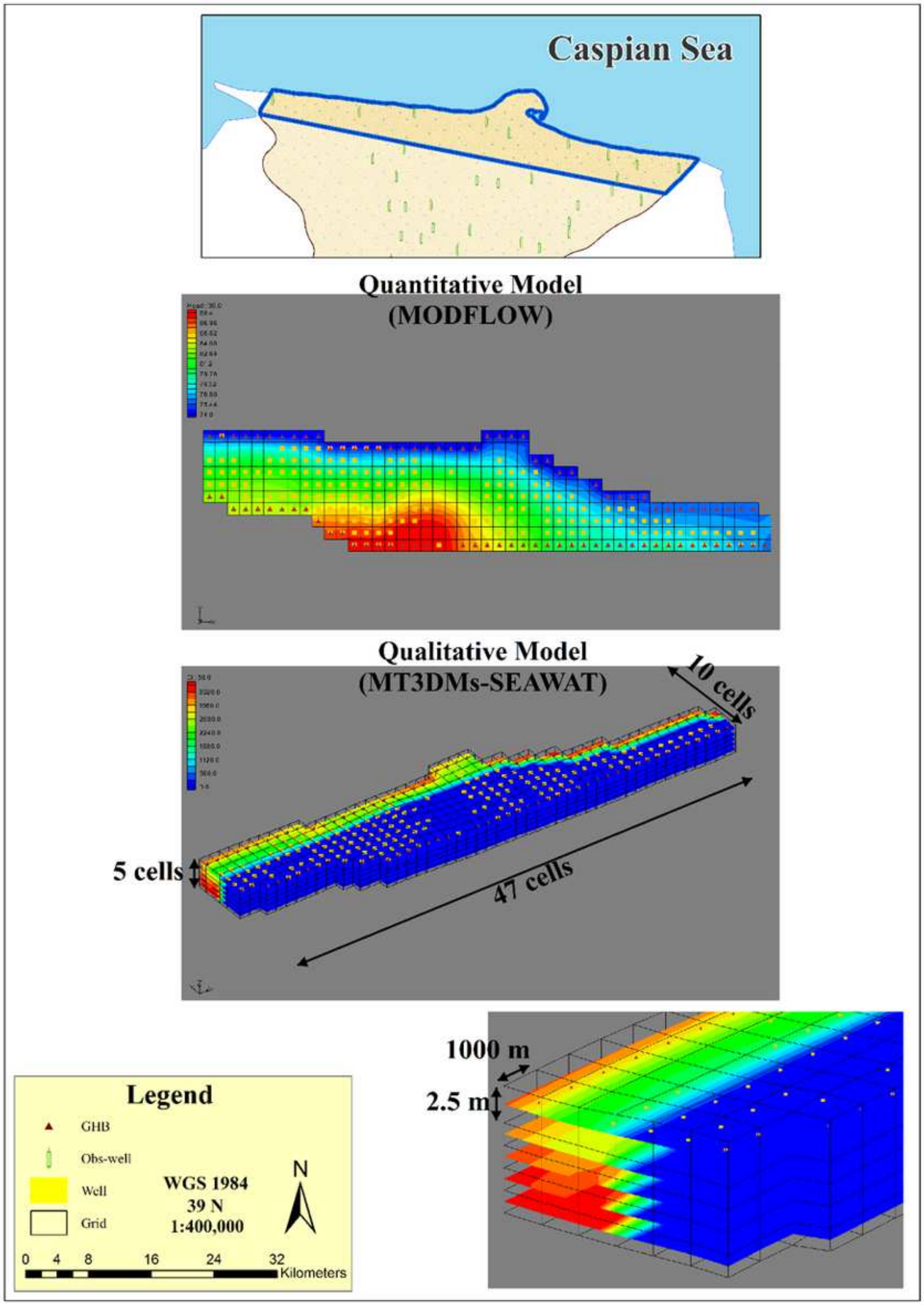


Figure 4

Study area and the conceptual model of the aquifer

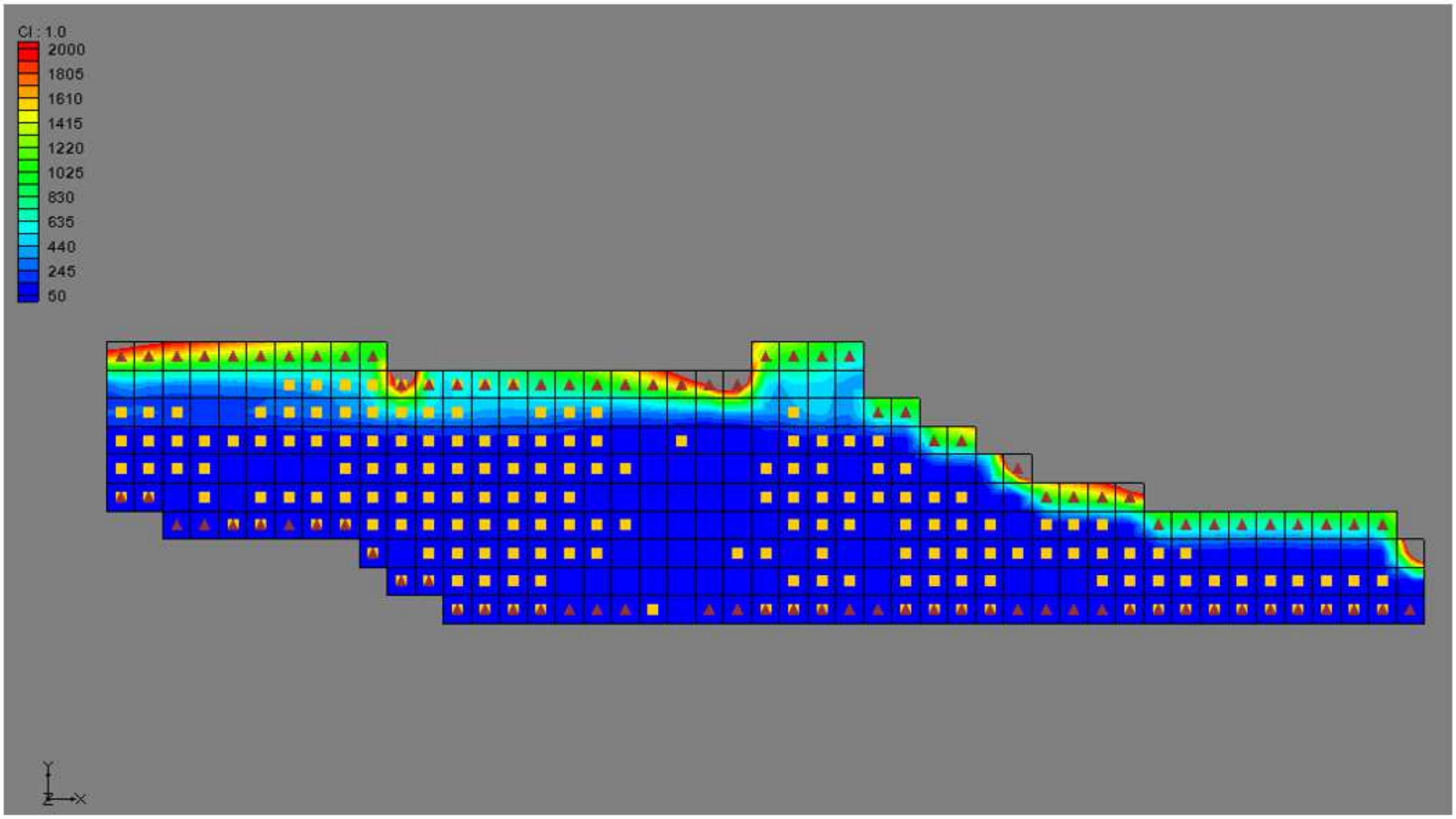


Figure 5

Simulation of the MT3DMs model in the aquifer outlet section

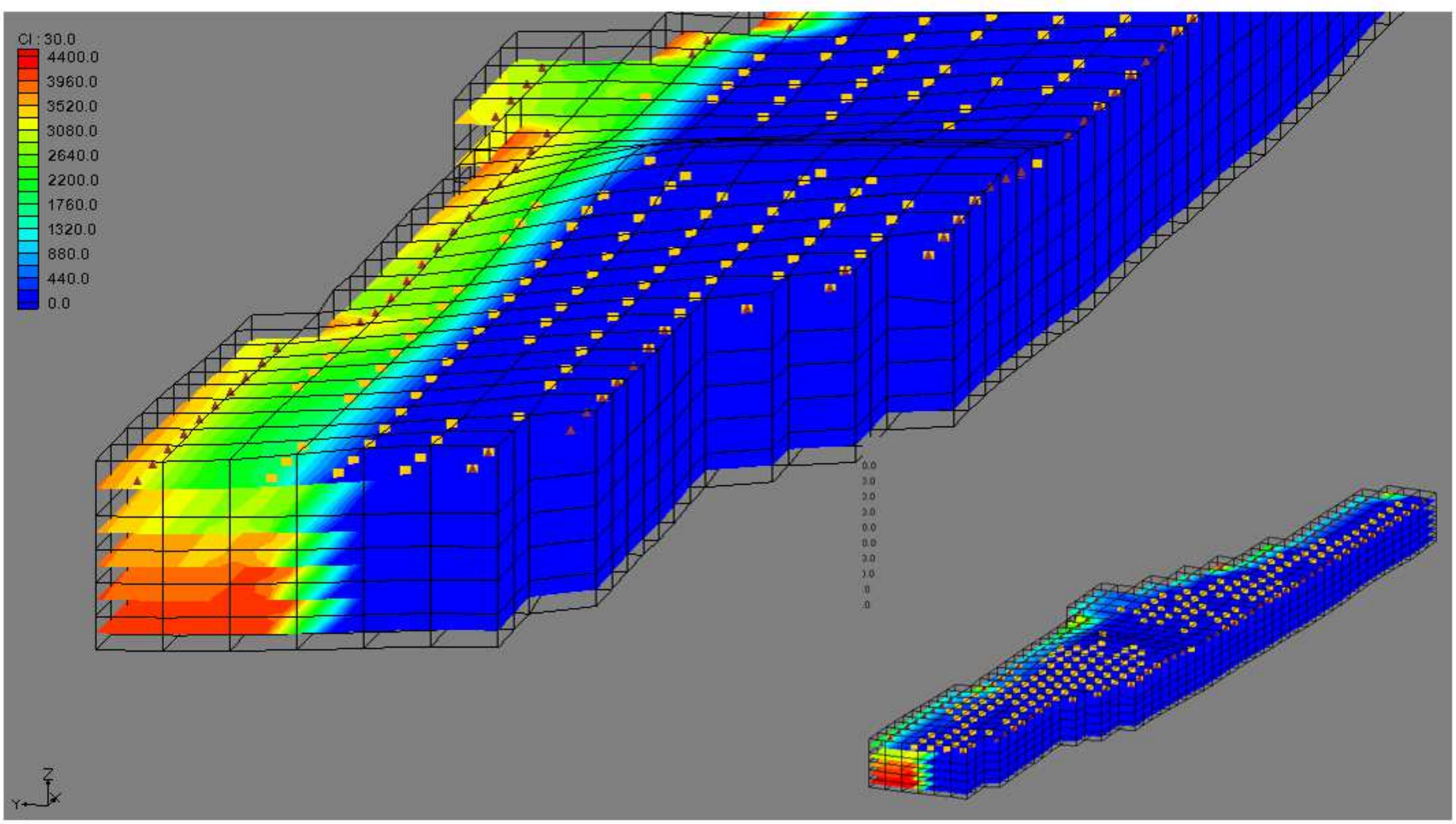


Figure 6

Three-dimensional view of saltwater and freshwater interface model in the aquifer outlet

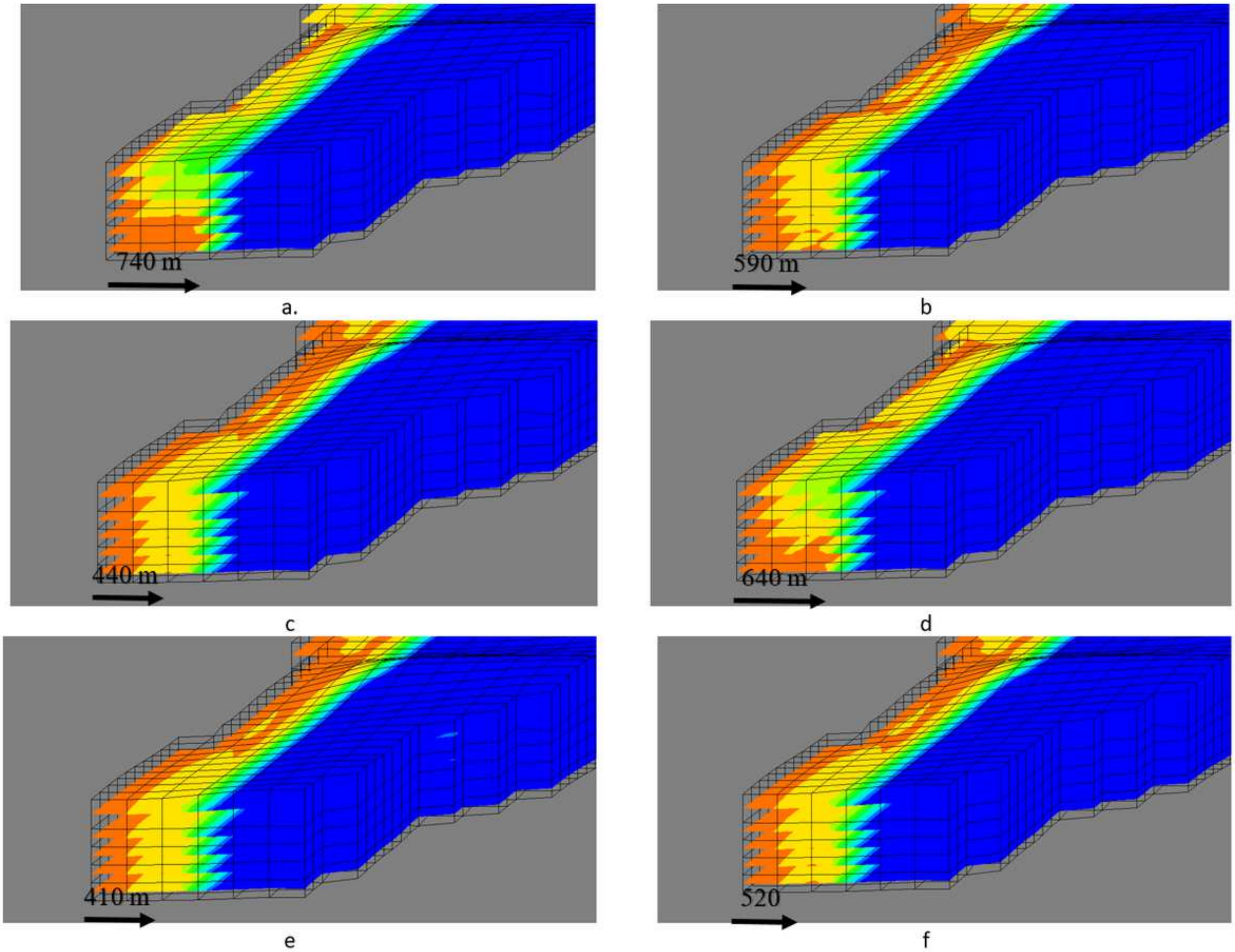
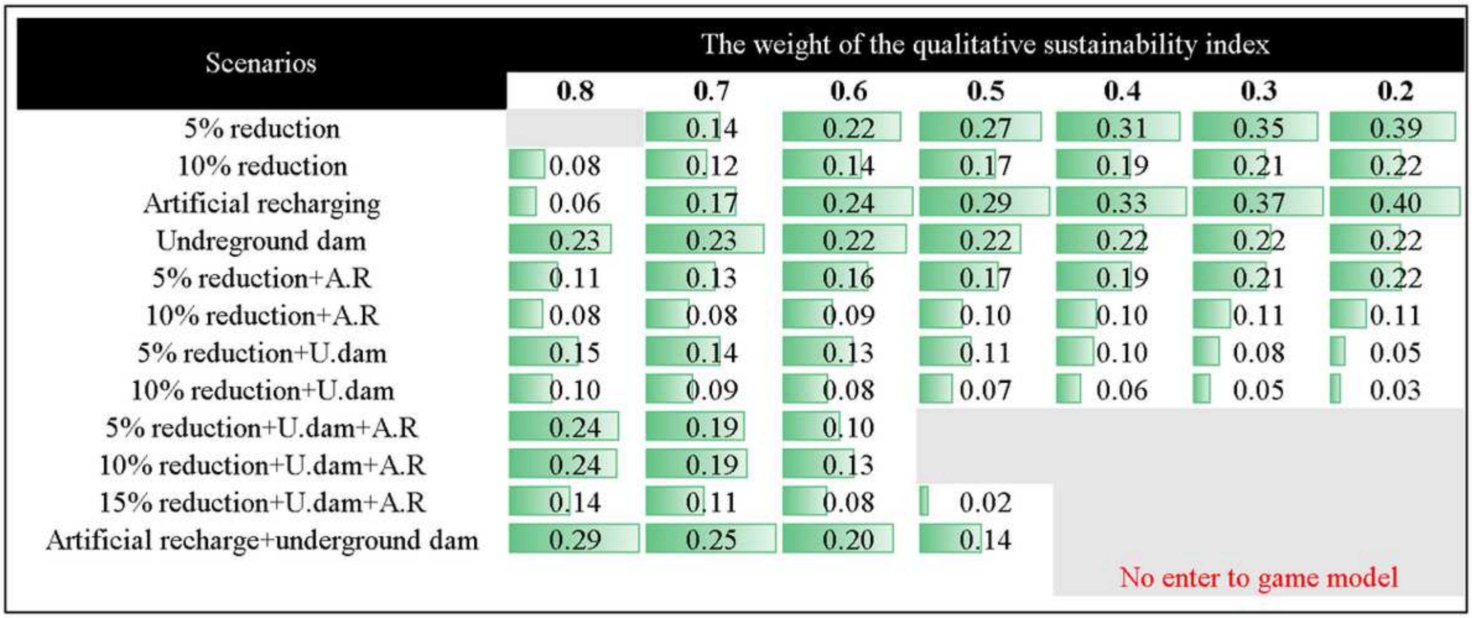


Figure 7

Results of saltwater intrusion by SEAWAT model from the sea for the all strategies: a) Business as usual b) Artificial recharge c) Underground dam d) 5% Exploitation reduction e) Underground dam + Artificial recharge f) 5% Exploitation reduction + artificial recharge



Scenarios	The weight of the qualitative sustainability index						
	0.8	0.7	0.6	0.5	0.4	0.3	0.2
5% reduction		0.14	0.22	0.27	0.31	0.35	0.39
10% reduction	0.08	0.12	0.14	0.17	0.19	0.21	0.22
Artificial recharging	0.06	0.17	0.24	0.29	0.33	0.37	0.40
Undreground dam	0.23	0.23	0.22	0.22	0.22	0.22	0.22
5% reduction+A.R	0.11	0.13	0.16	0.17	0.19	0.21	0.22
10% reduction+A.R	0.08	0.08	0.09	0.10	0.10	0.11	0.11
5% reduction+U.dam	0.15	0.14	0.13	0.11	0.10	0.08	0.05
10% reduction+U.dam	0.10	0.09	0.08	0.07	0.06	0.05	0.03
5% reduction+U.dam+A.R	0.24	0.19	0.10				
10% reduction+U.dam+A.R	0.24	0.19	0.13				
15% reduction+U.dam+A.R	0.14	0.11	0.08	0.02			
Artificial recharge+underground dam	0.29	0.25	0.20	0.14			

No enter to game model

Figure 8

Sensitivity analysis of the weight of qualitative sustainability and sustainability cost indices

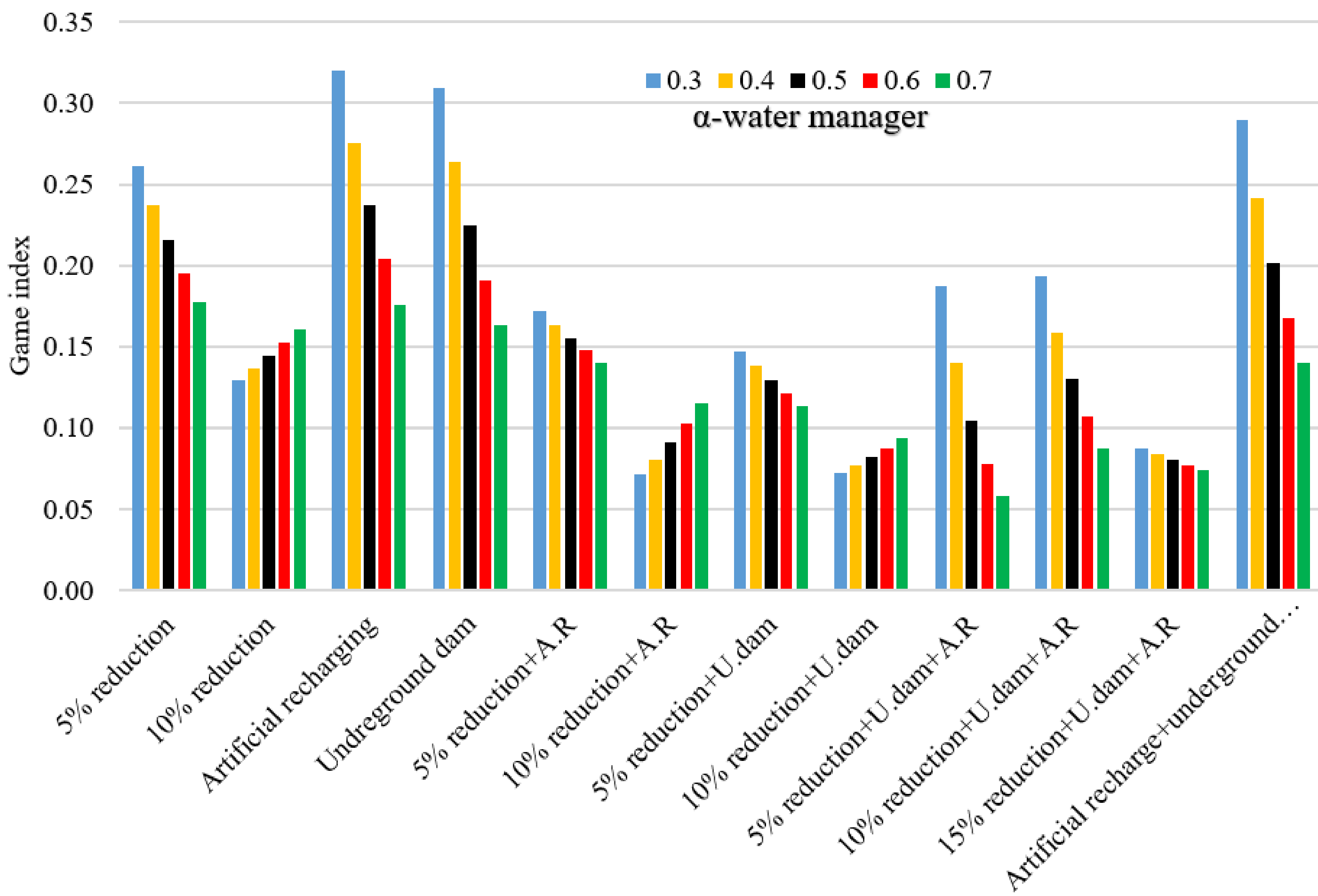


Figure 9

The sensitivity analysis of the relative power of the government in the conflict resolution model

Supplementary Files

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- GraphicAbs.png