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Investigating the vulnerability of the northern coasts of Iran due to changes in the water level of the Caspian Sea by considering the effects of climate change

Sina Ghassabian[a], Omid Tayari[b,*], Mehdi Momeni Roghabadi[c] and Mohsen Irandoost[c]
[a] Faculty of Engineering, Azad University, Kerman Branch, Kerman, Iran
[b] North Tehran Azad University, Tehran, Iran
[c] Kerman Branch Azad University Kerman, Iran
*Corresponding author. E-mail: omiid.tayarii@yahoo.com

ABSTRACT

Coastal aquifers are one of the most important sources of water supply, and it is expected that the effects of climate change will be one of their threatening factors in the short or long term. The present study was conducted in the northern coasts of Iran (Amirabad, Babolsar) and the main goal was to investigate the behavior of saltwater advance in coastal aquifers considering the changes in the coastline due to the effects of climate change and aquifer characteristics. In order to simulate the flow of underground water and the advancement of salt water in the coastal aquifer of the Caspian Sea, MODFLOW MT3DMS and SEAWAT numerical models were used in the GMS10.6 software. The results show that there is a salinity increase of up to 60 ppt, which is much higher than the minimum seawater salinity of 2 ppt. According to the results, it is clear that in the studied area, contaminated water entered the underground aquifers, especially in the coastal erosion areas and during the seasons when the sea level changes and when the changes in the coastline increase.

Key words: Caspian Sea, climate changes, coastal aquifer, coastline changes, GMS, saltwater

HIGHLIGHTS

- Investigated the vulnerability of the aquifer by considering the changes in the water level due to climate change.
- For this purpose, the images in the GIS environment were drawn to create a conceptual model.
- After georeferencing the images, the values are assigned and then transferred to the GMS software.
- It can be seen that the amount of water pollution increases every month.

1. INTRODUCTION

Water level fluctuations of the Caspian Sea have been very complex and unknown throughout history and have undergone asymmetric and severe changes in a way that, in the last 40 years, it has increased and decreased by 2.5 and 1.3 m, respectively. The climate changes and, as a result, the drastic changes in the water fluctuations of the Caspian Sea have had a great impact on the population, economy, and development of the region and brought many environmental, economic, and social problems. One of the most important options for the fluctuation of the Caspian water level is the change in the amount of incoming and outgoing water, which includes the inflow of river and underground water, precipitation and evaporation from the sea level, and the outflow of water to the bays. Among the above-mentioned factors, Volga flooding and evaporation from the sea level are very important. The water of the rivers entering the Caspian Sea is mainly supplied from the Volga (about 80%) and other rivers of the northern, western, and southern coasts (Ural, Terek, Sulak, Samur, Mtkvari, Sefidroud). So far, various predictions have been made regarding the fluctuations of the Caspian Sea water level. For example, the prediction of the increase in the water level in the next 3 years by about 42 cm is one of the things investigated in this research. Based on the latest information on the changes and the average water level of the Caspian Sea, which was obtained by the National Center of Caspian Sea Studies (Caspian Sea Quarterly 2016) using the Caspian Sea Quarterly, the water level of the Caspian Sea in the first half of the water year 2016–2017 reached –27 m by the end of March 2017, which was an increase of 7 cm compared to the previous year at the same time (Figure 1).

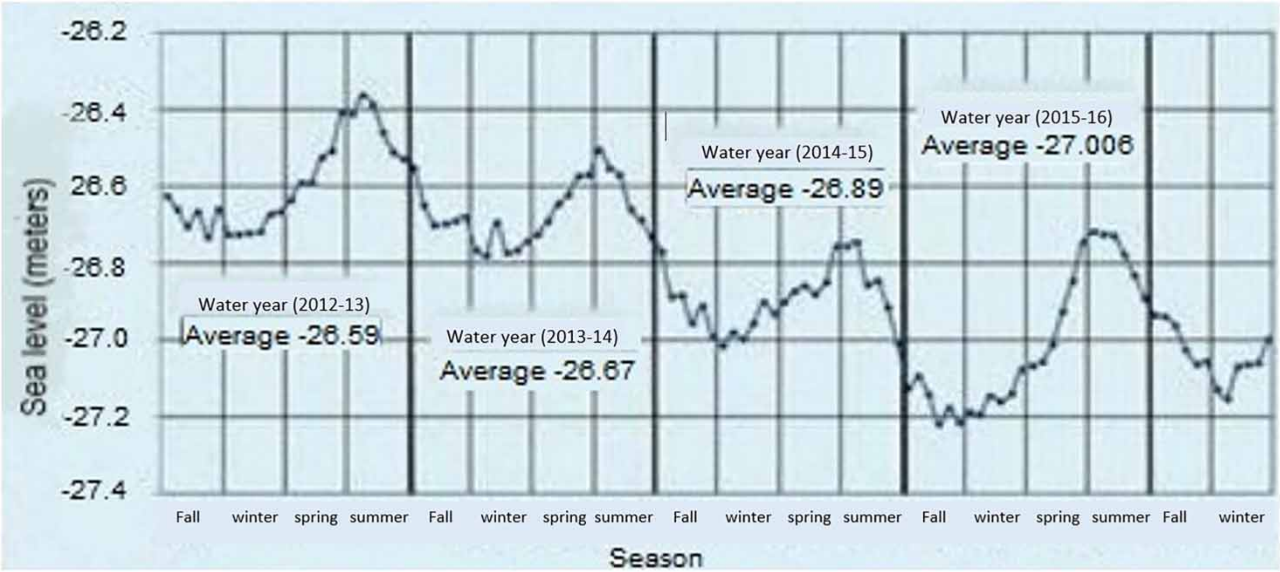

Figure 1 | Water level changes from the water year 2012 to the water year 2017.

The advance of salt water in coastal aquifers has become one of the problems of water resources management due to the high volume of extraction from underground water sources in these areas and due to the exploitation capabilities and potentials. In coastal areas, fresh water aquifers have a hydraulic relation with salt water, the direction of flow toward the sea or the ocean is established depending on the level of underground water. The change in the level of water causes the reversal of the underground water flow and this causes the salty water fronts to enter the aquifer. So far, extensive studies have been conducted on the changes in the water level of the Caspian Sea and the changes in the coastlines (Khoshravan 2007; Kordavani 2014) as well as the changes in the coastline of the southern shores of the Caspian Sea during the period 1978–2015 (Tharvati (2017). Today, these aquifers are in danger due to the advance of salty sea water toward them, exposing them to a lot of pollution, thus this advance has made the water taken from the aquifers unusable for a long time due to salinity (Ketabchi *et al.* 2014a, 2014b). The progress of salt water in coastal aquifers is a natural process that occurs due to the difference in the density of salty water and fresh water. This advance takes place from the side of the sea water which contains salty water toward the coastal aquifers which has fresh water and creates an advance claw. The extent of advance can vary from several meters to several kilometers (Ketabchi *et al.* 2013; Laattoe *et al.* 2013; Mahmoudzadeh 2013). In the coastal aquifers of northern Iran, the phenomenon of salt water advancing in the coastal aquifer is intensifying due to uncontrolled extraction of water from wells, tidal fluctuations, and the effects of climate change, which are more concerning today (Rajabi *et al.* 2011; Ketabchi & Ataie-Ashtiani 2015a, 2015b). Also, excessive withdrawal from the aquifer through wells causes subsidence and changes in the level of the beaches (Fathi & Noorian-Bidgoli 2022).

Climate change impacts have vast consequences in the water sector, increasing health risks, environmental pollution, and substantial economic impacts (Ratnaweera *et al.* 2022). Climate change is one of the important and influential factors on the phenomenon of salt water advance. According to the latest report of the Intergovernmental Panel on Climate Change (IPCC 2013), we find that coastal aquifers are more vulnerable due to climate change factors, including sea level rise, changes in feeding rates, and changes in the coastline, and similar issues. It makes it important to investigate and study the extent of saltwater advance in coastal aquifers, which is stated in the study by Ketabchi & Ataie-Ashtiani (2015b). In 2016, Ketabchi *et al.* (2016), researched problems in the field of climate change and the effects of climate change in the management of underground water resources. In the conducted studies, 0.5–4 m of sea level rise has been predicted until the end of the 21st century (Vermeer & Rahmstorf 2009). The review of the conducted studies shows that initially most researchers focused on simulating the phenomenon. Researchers have studied the advance of salt water and the investigation of its aggravating factors, but the effect of sea level changes on it is less researched; however, in recent years, this issue has become more important. Chang *et al.* (2011) conducted a study on an aquifer (unconfined and confined) in Australia and were able to introduce a natural response mechanism of the groundwater system to sea level rise. It should be noted that the flow simulations in the confined aquifer shows a return mechanism that returns the advancing wedge to its initial point, but in the unconfined aquifer, this mechanism is negligible. Ataie-Ashtiani *et al.* (2013) shows that in many studies, the combined effect of sea level rise and coastline changes is ignored, also in shallow and unconfined coastal aquifers, shoreline changes significantly widen the advance of salt water. Also, the results of the study show that in some cases the effect of changes in the coastline will be more important than other factors. In the study of Mahmoudzadeh *et al.* (2016), the characteristics of environmental changes caused by climate changes and the scenarios of changes in feeding rate and sea level rise in groundwater management were discussed. In their research, Rezapour & Saghravani (2016) investigated how saltwater advances under the conditions of aquifer water table reduction. The results of their investigation showed that the two factors of difference in density between salt and fresh water and reversed hydraulic slope cause salty water to advance into the aquifer. Fathi Zaad *et al.* (2017) investigated the location of the common boundary of salty and fresh water under the Talar Basin using the SHARP model, which is a quasi-3D numerical finite-difference model that simulates freshwater and saltwater flow separated by a sharp interface in layered coastal aquifer systems. The results of their research showed that in the western areas below the Talar area, salty water penetrated into the aquifer up to 5.4 km from the coastline. Also, in the central areas, the advance of salt water is about 5.2 km from the coastline. Kardan Moghadam & Banihabib (2017) investigated the environmental effects of the influx of salty water fronts into the Sarayan aquifer located in South Khorasan province. The results of this research showed that it is necessary to manage underground water withdrawal using the management scenario of reducing water withdrawal from underground sources in order to improve the water quality of underground aquifers and prevent the influx of salty water. Ketabchi *et al.* (2016) researched the effects of climate change, including sea level rise, feeding rate changes, and their combined effects on underground water resources. In this research, comprehensive investigation of the influencing factors, including the environmental and physical conditions of the aquifer in groundwater problems, and their combined effects in modeling the problem was carried out. One of the problems of this research is considering the real effects of climate change phenomena such as the gradual increase in sea level, uncertainties, and its effects in decision-making models. Based on the summary of the studies conducted, it can be said that in order to manage underground water resources and to know how these valuable and vital resources are influenced by various factors such as climate change and changes in the coastline and aquifer characteristics, it is important and necessary to consider these factors and their combined effects. Modeling brings the problem closer to real conditions. The underground water flow model is a set of differential equations (Kentel *et al.* 2005). Finite difference equations and finite elements are one of the most important and widely used methods in solving underground water problems and for evaluating complex underground flows and the reaction of heterogeneous, unstable, and heterogeneous aquifers with wells, multiple pumping, and complex boundary conditions (Cobaner *et al.* 2012).

Due to the fluctuations of the underground water level and the high uncertainty in the calculations of the hydrodynamic coefficients of the aquifer, it is important to conduct detailed hydrogeological studies and determine the role of each of the parameters affecting the groundwater flow (Nasiri *et al.* 2021).

2. MATERIALS AND METHODS

2.1. Study area

The area under this research study is located in the north of Iran between Amirabad port and Babelsar port, which is located between the geographical longitudes of 52°35′ to 54°44′ East and 35°44′ to 36°52′ North. The area of this area is 10,240 km^2, of which 1,810/551 km^2 are plains and the rest are highlands. The four main rivers of Tejn, Telar, Nekarud, and Syahrud feed the coastal aquifer. The highest point of this range is 3,929 m and the lowest point is −26 m above the Azad sea level at the outlet of the basin. The study area is from the north to the Caspian Sea and the study area Behshahr-Bandargaz leads from the south to Semnan and Firouzkoh study area is from the west to the Babol-Amol area and from the east to the Gorgan area. The general trend of the underground water level curves in the east–west plain and the distances of the level curve of the underground water level in the alluvial and southern lands are low and the hydraulic slope of the underground water is high. As we move toward the north, in the middle lands of the plain, the distances of the curves increase and the hydraulic slope of the underground water decreases. There are 73 active meteorological stations in the research area. The values of annual distribution of rainfall, evaporation, and temperature during the statistical period of 45 years (1966–2011) are equal to 664 mm (Sari-Neka) and 713 mm (Qaemshahr-Joibar); 1,176.4 mm (Sari-Neka) and 1,060.34 mm (Qaemshahr-Joibar); and 16.51 °C (Sari-Neka) and 15.94 °C (Qaemshahr-Joibar) (Ministry of Energy, Regional Water Company of Mazandaran 2014a, 2014b). The study area is shown in Figure 2.

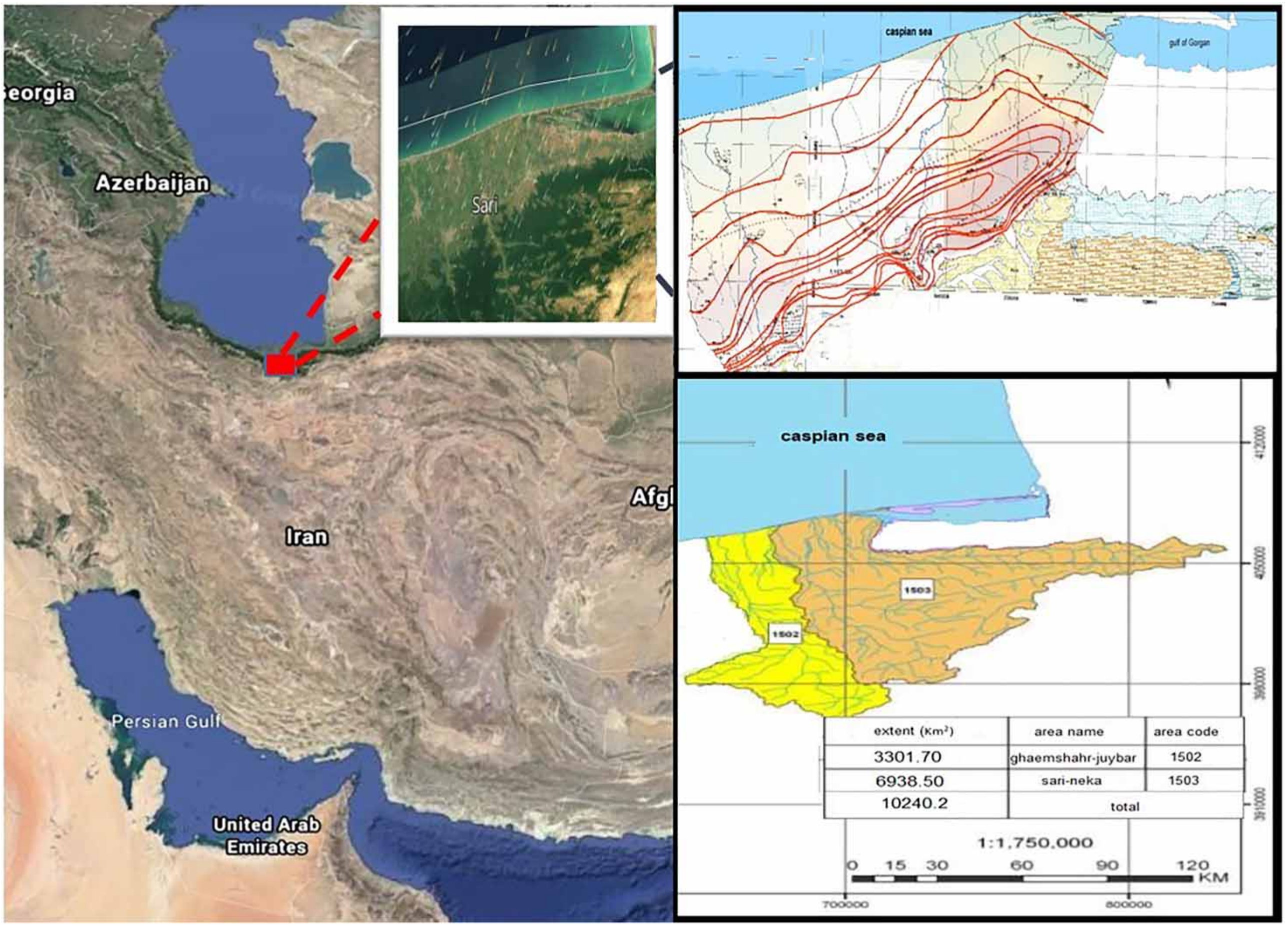

Figure 2 | The study area.

2.2. Research method

In this research, we first drew the images in the geographic information system (GIS) environment to build a conceptual model, and after georeferencing the images, we assigned values and then converted them into points and transferred them to the groundwater modeling system (GMS) 10.6 software. Finally, using the MODFLOW model, a quantitative assessment of the underground water resources was done and the obtained results entered into the MT3DMS model to simulate the transfer of salinity by considering the process of transfer, dispersion, and diffusion. Finally, the outputs of the MT3DMS model are entered into SEAWAT, which is a model for simulating salinity transfer by considering density changes. Finally, we examine the impact of changes in the coastline during the advances of saltwater to groundwater in the study area.

2.3. Governing equations

2.3.1. Governing equation for flow in terms of freshwater head

In this research, in GMS10.6 software environment, the SEAWAT numerical model was used, which can simulate three-dimensional (3D) underground water flow considering the flow density in the porous medium. The basic concept of this numerical model is the combination of MODFLOW (Harbaugh *et al.* 2000) groundwater flow simulation software and MT3DMS (Zheng & Wang 1999) pollutant transport simulator into a single program to solve the groundwater flow equations depending on the density and pollutant transport. MODFLOW is a 3D finite difference model for simulating groundwater flow in steady state and transient conditions.

The governing equation for groundwater flow under the influence of density that is solved by MODFLOW in the SEAWAT model and is expressed as follows (Guo & Langevin 2002):

$$\frac{\partial}{\partial \alpha}\left\{\rho K_{f\alpha}\left[\frac{\partial h_f}{\partial \alpha}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial \alpha}\right]\right\}+\frac{\partial}{\partial \beta}\left\{\rho K_{f\beta}\left[\frac{\partial h_f}{\partial \beta}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial \beta}\right]\right\}+\frac{\partial}{\partial \gamma}\left\{\rho K_{f\gamma}\left[\frac{\partial h_f}{\partial \gamma}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial \gamma}\right]\right\}=\rho S_f\frac{\partial h_f}{\partial t}+\theta\frac{\partial \rho}{\partial C}\frac{\partial C}{\partial t}+\bar{\rho}q_s \quad (1)$$

where α, β, and γ co-ordinate axes are perpendicular to each other in the main permeability directions, $K_{f\alpha}$, $K_{f\beta}$, $K_f\gamma$ are hydraulic conductivities in three main directions (m/s), h_f is the fresh water head (m), Z is the height above the center of the model cell (m), ρ is the fluid density (kg/m^3), ρ_f is the freshwater density (kg/m^3), S_f is the storage factor (1/m), θ is the effective porosity (dimensionless), C is the solute concentration (kg/m^3), $\overline{\rho}$ is the density of the water entering from the supply source or exiting through the discharge source (kg/m^3), q_s is the volumetric rate of flow per unit volume according to the supply and discharge of water per unit of time (1/s), and t is the time (s).

2.3.2. Governing equation for solute transport

The MT3DMS numerical model has a structure similar to the MODFLOW model and is used to simulate changes in the concentration of dissolved pollutants, taking into account the process of transport, dispersion, diffusion, and chemical reactions. After developing and calibrating the flow model, the information needed to simulate pollution transfer (such as the volume of flow transferred between cells) is given to this model (Nazari & Joodavi 1979). By using the MT3DMS numerical model, the SEAWAT code solves the equations governing the transfer of saltiness, which are expressed as follows (Zheng & Bennett 2002):

$$\frac{\partial C}{\partial t}=\nabla.(D.\nabla C)-\nabla.(\bar{v}C)+\frac{q_s}{\theta}C_s+\sum_{k=1}^{N}R_k \quad (2)$$

where D is the coefficient of hydrodynamic dispersion (m^2/s), C_s is the concentration of solutes entering from the feed source or exiting through the discharge source (kg/m^3), and R_k is the ($k=1,\ldots,N$) rate of production or decomposition in the reaction K from N different reactions (kg/m^{3}s).

2.3.3. Concentration and density

In the simulation of density-dependent flow and solute transport, it is assumed that the fluid density is only a function of the solute concentration and the effects of pressure and temperature changes on the fluid density are ignored (Langevin *et al.* 2003). The linear equation for converting solute concentration to fluid density in the SEAWAT code is expressed as (Benjakul 2010):

$$\rho=\rho_f\frac{\partial \rho}{\partial C}C \quad (3)$$

Changes in $\partial\rho/\partial C$ fluid density to solute concentration $\partial\rho/\partial C$ depend on the unit selected by the user during the simulation process. For example, if the unit of meter and kilogram is used for simulation, the value is equal to 0.7143, which is approximately equivalent to the changes in fluid density divided by the solute concentration for fresh water and salty water.

2.4. Conceptual model and aquifer modeling

Figure 3 shows the process of modeling the groundwater condition of the studied plain with the help of GMS software in this research. MODFLOW, as a widely used mathematical model based on the law of continuity and conservation of mass, and it has been used to solve differential equations using the finite difference method for modeling the groundwater flow of the aquifer. In MODFLOW, the input data are prepared by GMS and stored as files and called from GMS during MODFLOW startup. Underground water modeling usually starts with the creation of a conceptual model and then ends with the use of a mathematical model. In fact, the conceptual model is a simplified model of the reality in the aquifer. In this research, with the cooperation of the Mazandaran Regional Water Company and using the statistics presentation system of the Ministry of Energy, input information such as the status of the water characteristics of the exploitation and observation wells in the region was carefully collected and entered into the software. For this purpose, information on water pumping wells located

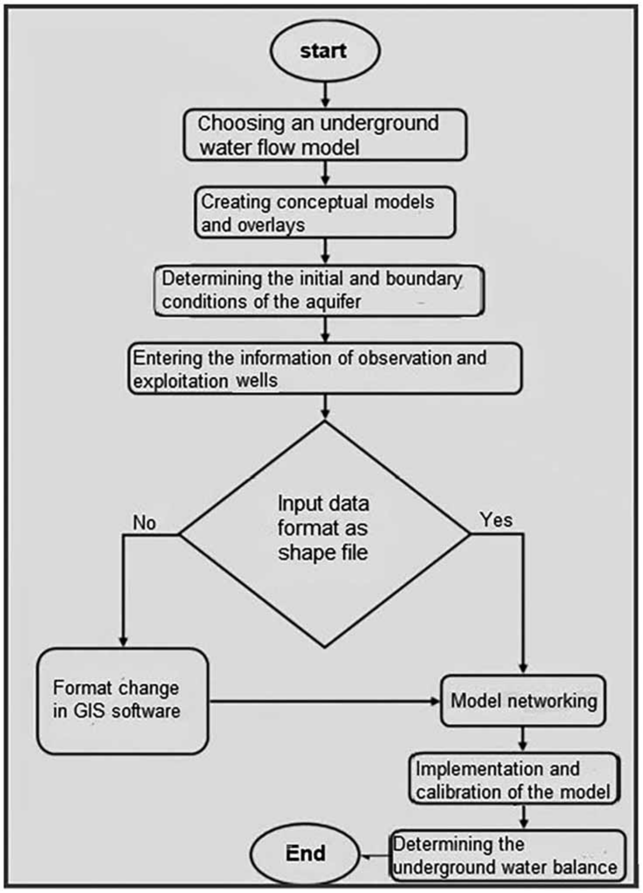

Figure 3 | The process of conducting the study and the process of numerical modeling of the aquifer by GMS software.

in the study area was collected and selected. These wells are authorized wells for water exploitation, and complete information was available. Therefore, unauthorized and abandoned wells whose information was not available were not been considered. In this research, all the layers and covers required for the conceptual model were prepared by GIS and then used in the GMS software environment to build the model. Figures 4 and 5 show the location of observation and exploitation wells, river cells, and input and output boundaries prepared by the GIS software. The conceptual model developed in this study is based on the changes in the water level of the Caspian Sea and changes in the feeding rate on the advance of salty water in the coastal aquifer. Figure 6 shows the conceptual model of this effect. As can be seen, it is expected that the rise in the sea level will cause more salty water to advance in the aquifer. The conceptual model of groundwater flow is a descriptive and integrated framework that can be used to analyze the data and information related to the hydrology of groundwater. The preparation of a conceptual model requires the accurate integration of data, information, and reports related to the aquifer and the flow of underground water in the study area (Nazari & Joodavi 1979). To build a conceptual model, we first drew the images in the GIS environment.

After georeferencing the images, assigned values and points were transferred to GMS and zoned (Figure 7).

The reference range we were looking for was plain. The necessary parameters for the conceptual model included the water level of the observation wells, the location and discharge of the exploitation wells, the discharge of the rivers, the topography of the land surface, bedrock, the modeling area, and the geometry of the aquifer. Estimating the hydrodynamic coefficients of the aquifer (hydraulic conductance and specific yield for the quantitative model and longitudinal dispersion for the qualitative model) and determining the amount of incoming and outgoing groundwater flows and determining any sources of feeding and discharging of the aquifer were among the other parameters required to prepare the conceptual model. After preparing the conceptual model, it was used for numerical modeling of the finite difference network with cells of 500 m $\times$ 500 m. In the next step, the geometry of the aquifer, which includes the boundaries of the model and the topography of the bedrock and the

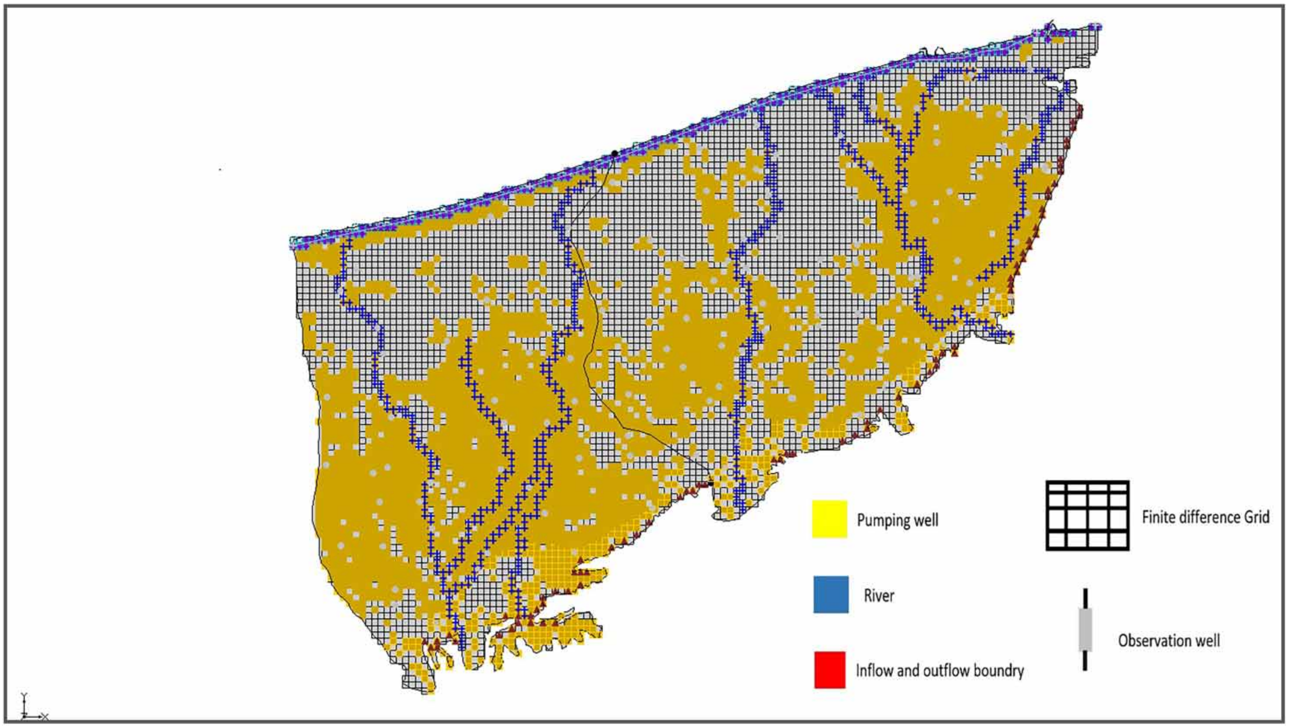

Figure 4 | Location of observation and exploitation wells, river cells and inlet and outlet boundaries.

surface of the aquifer, was applied to the model using interpolation methods. The height level layers of the earth's surface were extracted from digital elevation model data and by using interpolation, all points were directly generalized to the model grid. The altitude layer of aquifer bed rock was also created with the help of ground level data difference and aquifer thickness changes map and entered into the model through interpolation.

Modeling of the aquifer in steady state for October 2016 and in transient state for a period of 3 years including 28 periods of stress from November 2016 to February 2019 was considered. October was chosen to start the modeling due to the low fluctuation of the underground water level and the balance between the feeding and discharge of the aquifer in the first month of the water year. During this period, the model was recalibrated and validation was done for a 1-year period from October 2016 to September 2017. By drawing the groundwater hempotential map in ArcGIS 10.8 software using the groundwater level statistics of observation wells in October 2016 and applying it to the model cells through interpolation, the initial conditions of the model were determined. The inlet and outlet boundary of the aquifer, the flow intensity depending on the hydraulic load of GHB was taken into consideration. The southern parts of the aquifer were considered as the inlet boundary and the northern part of the aquifer, where the surface flows of the rivers in the study area discharge to the sea, was considered as the outlet boundary. Hydraulic conductivity in the aquifer range was applied to the model according to the aquifer compatibility map and the aquifer thickness map. Due to the heterogeneity of the aquifer and the different geological texture of the region in different places, the intended study area was divided into several areas for the purpose of hydraulic conduction and specific yield.

In transient conditions, the values of specific yield were estimated based on the results of the pumping test and according to the studies of Jabari and colleagues (Jabari *et al.* 2009). Figures 8 and 9 show the distribution of the optimal values of hydraulic conductivity and specific yield in the aquifer after the calibration stage, respectively. Based on these results, in the studied area, the values of hydraulic conductivity vary between 200 and 5,000 m per year, and specific yield varies between 0.25 and 0.55. The amount of infiltration from rainfall on the surface of the plain is also calculated to be 149,730 mm, which includes 21% of the rainfall of the plain (Ministry of Energy, Regional Water Company of Mazandaran 2014a, 2014b). In addition, according to the texture of the soil of the plain, the condition of the plot, and the irrigation method, 30% of the harvesting rate of the agricultural wells was reduced and it was applied to the model under the title of feeding through agricultural

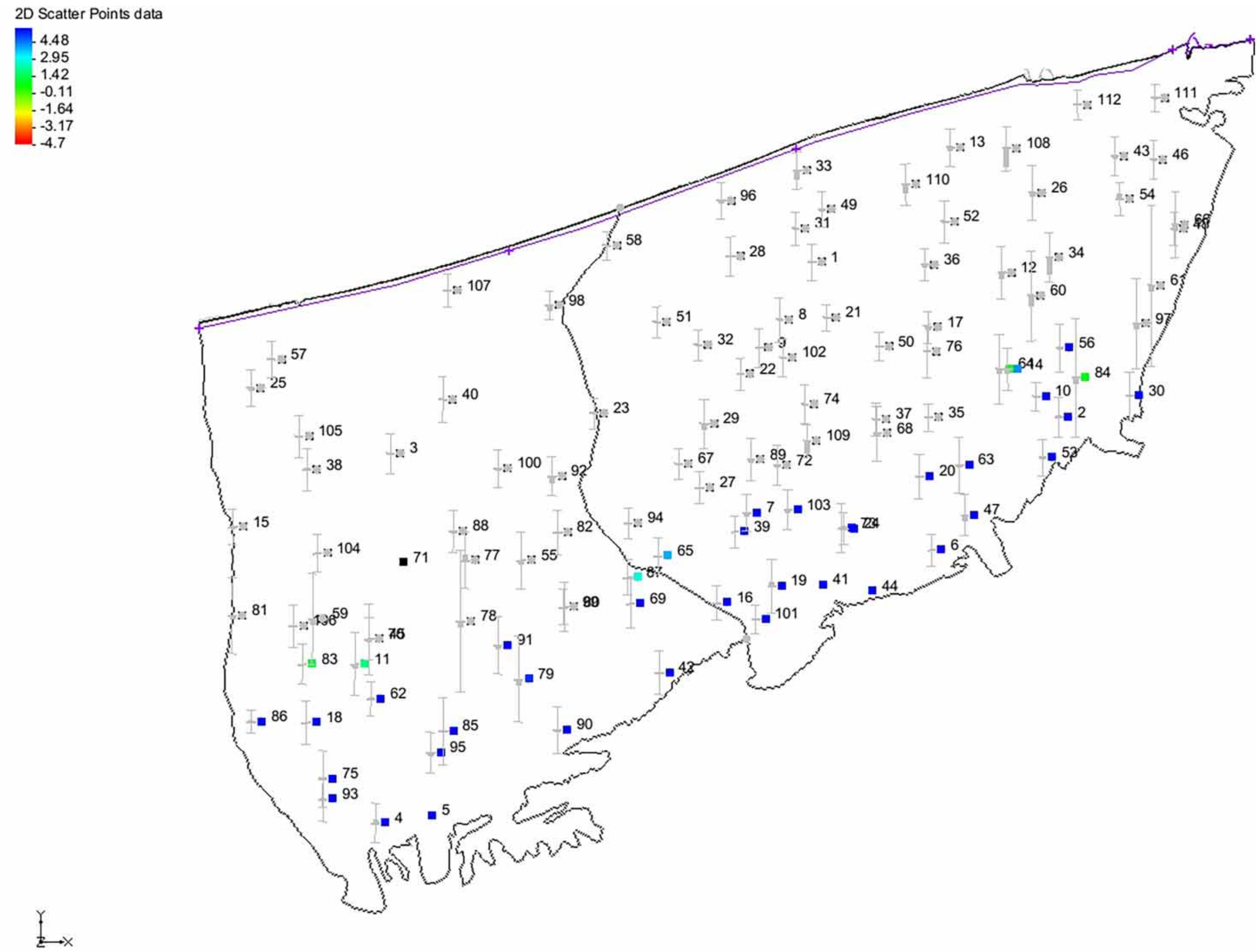

Figure 5 | Location of 112 observation wells in the study area.

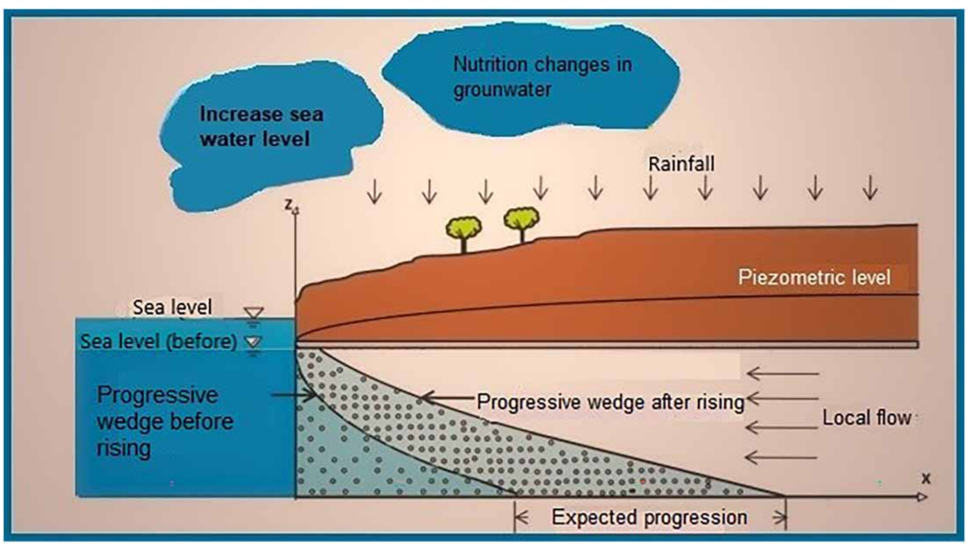

Figure 6 | Conceptual model of the effect of sea level rise and groundwater recharge rate changes on salty water development.

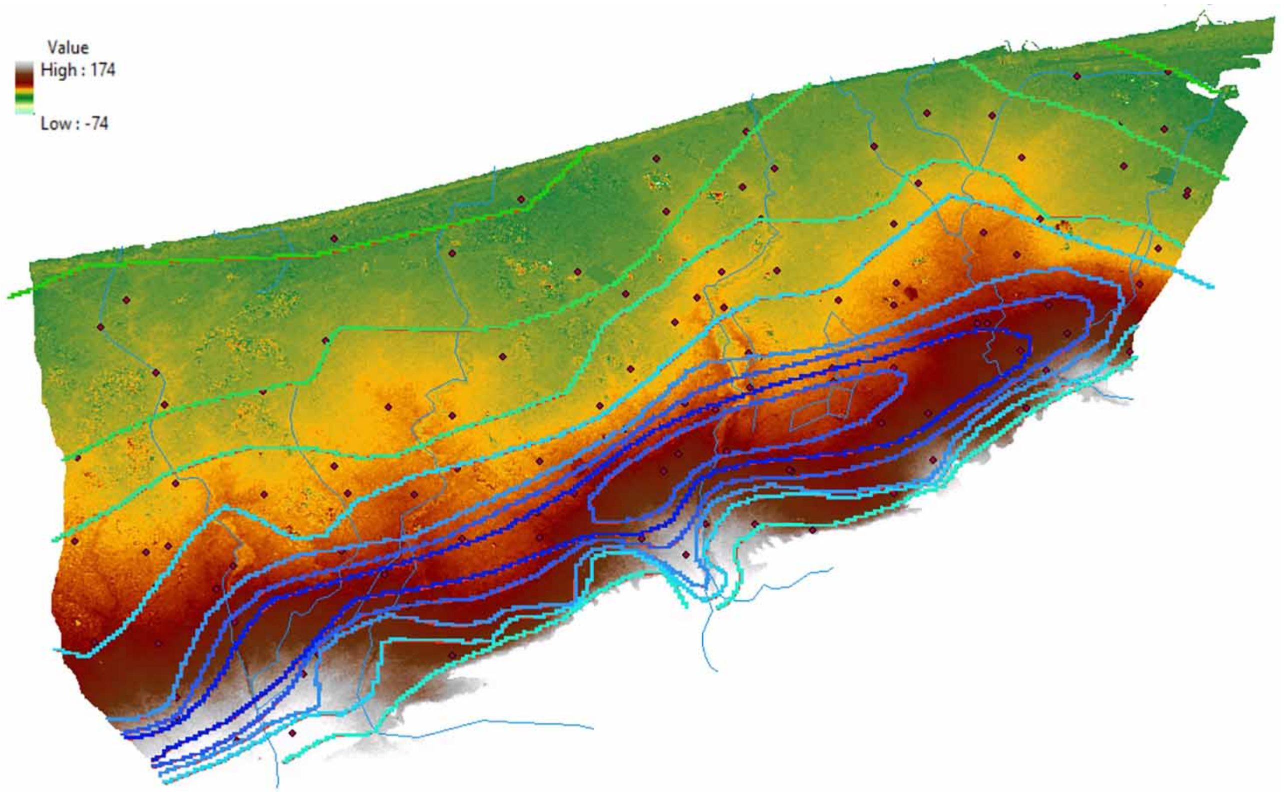

Figure 7 | Building a conceptual model in GIS.

return water (Ministry of Energy, Regional Water Company of Mazandaran 2014a, 2014b). Due to the variability of the aquifer's feeding and discharge components in different periods of stress, in the simulation of the non-permanent state, these values will be different for each period of stress. In the plain, due to flooding, there is no evaporation from the underground water during the agricultural season (rice is the dominant crop in the region). According to this point, evaporation from underground water does not take place, so we do not consider evaporation and transpiration during the agricultural season. During other seasons, the amount of evaporation from underground water is equal to 4.1 million cubic meters for the study area of Qaemshahr-Joibar and 9.78 million cubic meters for the study area Sari-Neka (Ministry of Energy, Regional Water Company of Mazandaran 2014a, 2014b). The characteristics of the rivers to enter the numerical model were extracted according to the border maps and river bed and water levels in the water resource balance reports of the region and were applied in the model. Figure 4 shows the position of exploitation and quantitative observation wells, active and inactive cells, borders and cells related to the river.

After building, calibrating, and validating the flow quantitative model, the groundwater qualitative model was prepared in the MT3DMS software. SEAWAT and MT3DMS are a subset of MODFLOW as post-processing, and the combination of MT3DMS and MODFLOW becomes SEAWAT; their results are in the GMS. In a qualitative model like the underground flow model, boundary conditions need to be defined. The boundary conditions considered in this model included circles in the upper part of the aquifer and in the entire area at the border of the coast and the sea (Constant-Head boundary (CHD) in MODFLOW). Once the concentration of seawater salinity was determined, which corresponded to the beginning of the modeling, we checked whether this salinity affected our study area over the following months. According to the obtained results, such penetration occurs in parts of the aquifer. According to the arrows that show the direction of the flow (Figure 10), we saw that in most cases, the water passed from the coast to the sea (due to the slope of the region and the presence of water resources such as rain). However, in some regions, the water receded in certain seasons and penetrated the underground water table. The sewage, salinity, and waste materials in sea water causes pollution and affects the aquifer. In the qualitative model that investigated the phenomenon of solute transfer in underground water, like the underground flow model, boundary conditions need to be defined. The boundary conditions considered in this model include

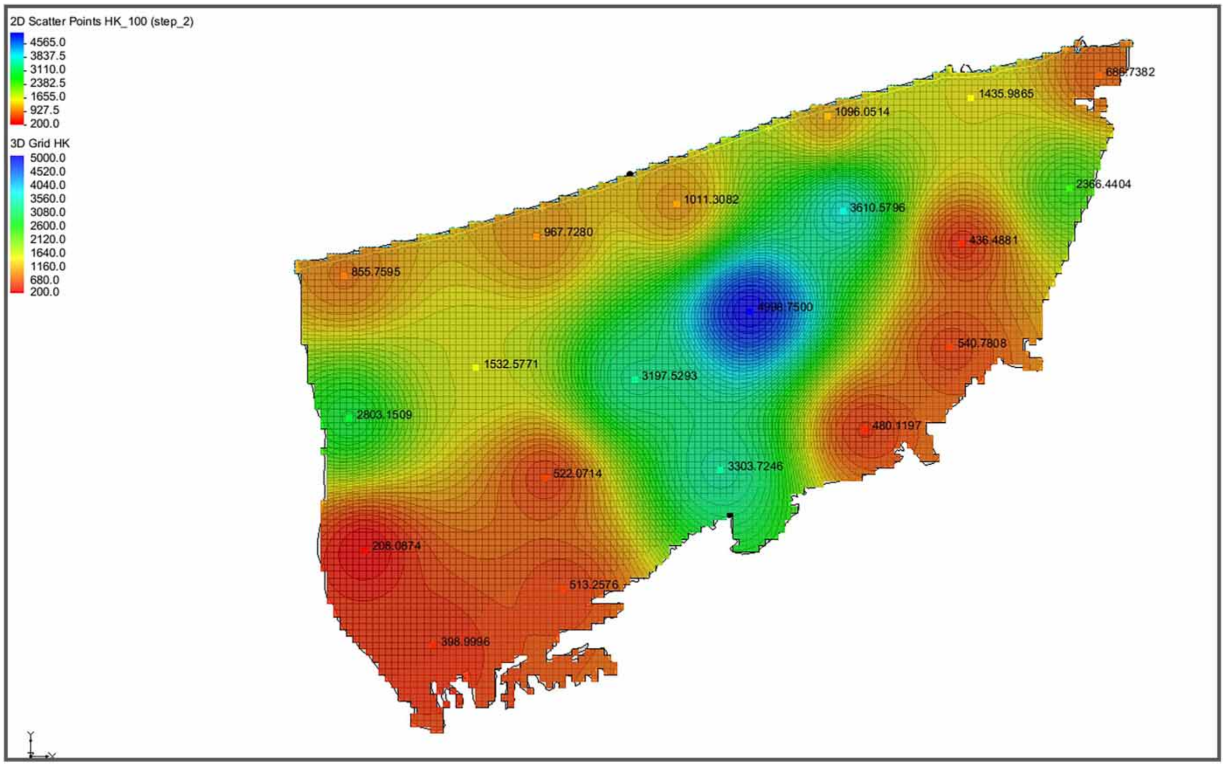

Figure 8 | Zoning of hydraulic conductivity values.

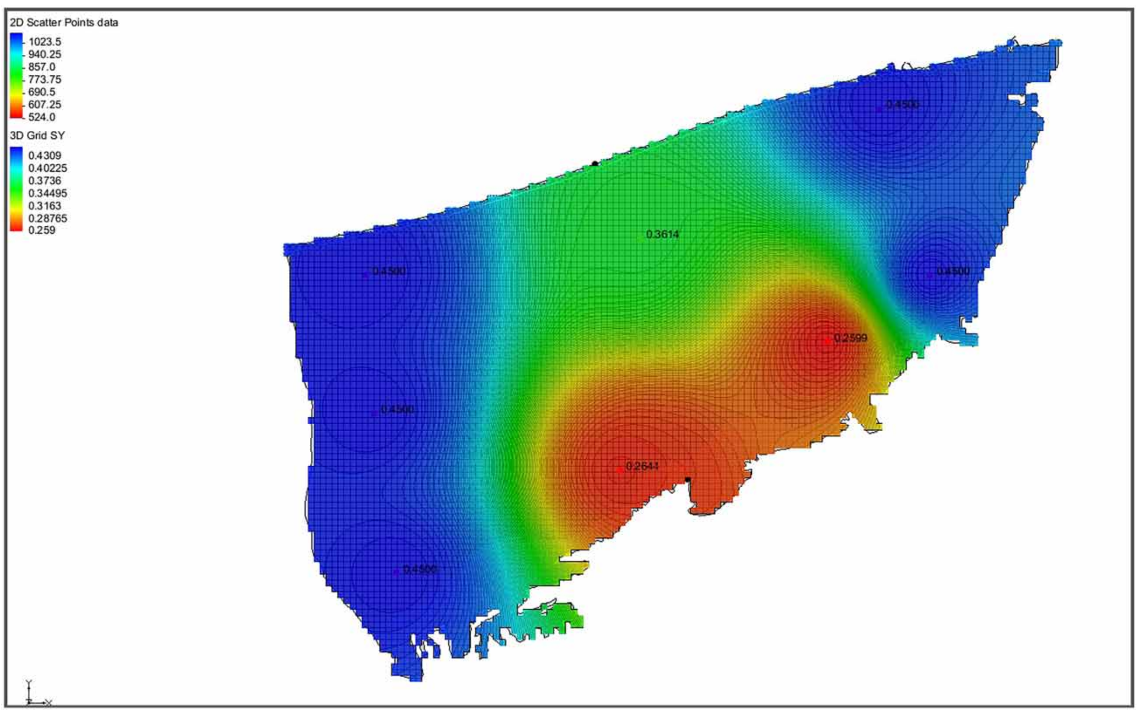

Figure 9 | Zoning of specific yield values.

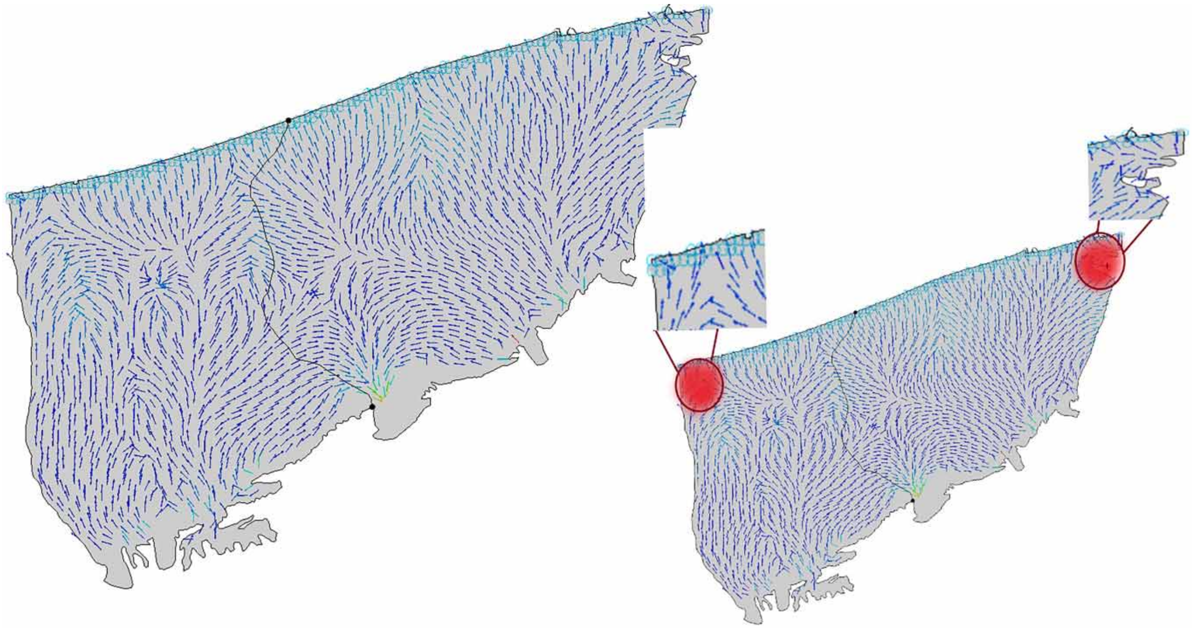

Figure 10 | The direction of the round trip flow from the aquifer to the sea and vice versa.

the boundary with a certain initial concentration that is applied in the entire range of the model and is related to the start of modeling. The porosity value at the beginning of the simulation in the entire range of the model is equal to 0.35 and the diffusion coefficient molecular equal to $10^{-9}\,m^2$ per second. In addition, information such as the scope of the model implementation, grid, and topography of the ground surface and bedrock is the same as the quantitative model. The qualitative temporal division of the aquifer was carried out weekly from October 2016 to February 2019.

3. RESULTS AND DISCUSSION

3.1. The results of calibration and validation of the model

In a groundwater model, we face various uncertainties. The most important parameters that create uncertainty in the simulation are the hydrodynamic parameters of the aquifer (hydraulic conductivity and specific yield), which should be properly zoned and appropriate values used (Abedi Koupai & Golabchian 2015). Based on this, the model was first implemented and recalibrated using the relevant water level data in steady state for the time step of October 2016, and then in the transient state during the period from October 2016 to February 2019. Calibration was done by a trial-and-error method using the water level data related to this statistical period in order to minimize the difference between observational and calculated water level at the location of the observation wells. There were limited changes in the parameters of hydraulic conductivity and specific yield. It should be noted that the results of the recalibrated model in the steady state are considered as initial conditions in the simulation of the transient state. Figures 8 and 9 show the zoning values of hydraulic conductivity and specific yield. According to Figures 8 and 9, it is clear that the values of these parameters are different in different regions, which indicates lower permeability and smaller size of soil particles in parts of the aquifer. The comparison of the observed values against the calculated values of the underground water level in the period of steady state and transient state calibration is presented in Figure 11(a) and 11(b). The obtained results show an acceptable agreement between the calculated and observed values. The comparison of the observed values against the calculated values of the groundwater level in the validation period is presented in Figure 12. The statistical error rate of the model in the calibration and validation stage is given in Table 1. The amount of statistical errors estimated in the simulation of the quantitative model with the presence of 112 observation wells indicates the accuracy of the built model. To observe the impact on the reduction of the static level of the aquifer, precipitation, return flow, pumping, hydraulic conductivity, storage coefficient, and hydraulic conductivity was examined by sensitivity analysis (Figure 13).

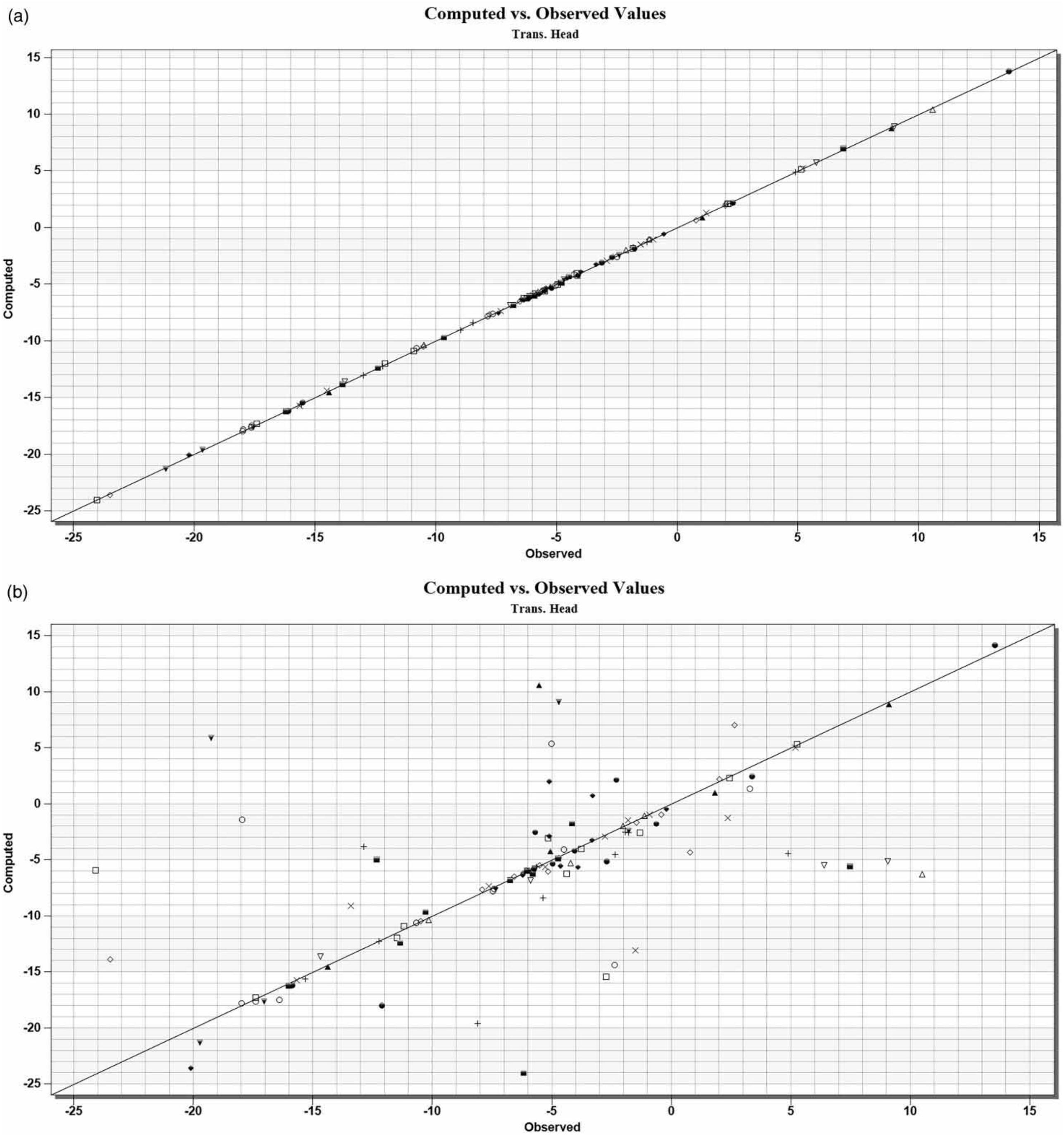

Figure 11 | Comparison of observational and calculated water level in flow model calibration (a) steady state flow model, (b) transient state flow model.

By examining the results and according to the available data, the most sensitive factors affecting the static level of the aquifer are return flow, pumping, hydraulic conductivity, permeable boundaries, storage coefficient, and specific yield.

Figure 14 shows the calibration error value and the acceptable error value compared to the observed and calculated values for observation well numbers 30, 36, 48, and 67, with proper distribution on the aquifer level in all stress periods. In addition, in Figure 15, the observed and calculated water level during the time of transient state calibration at the location of four observation wells 30, 36, 48, and 67 are presented.

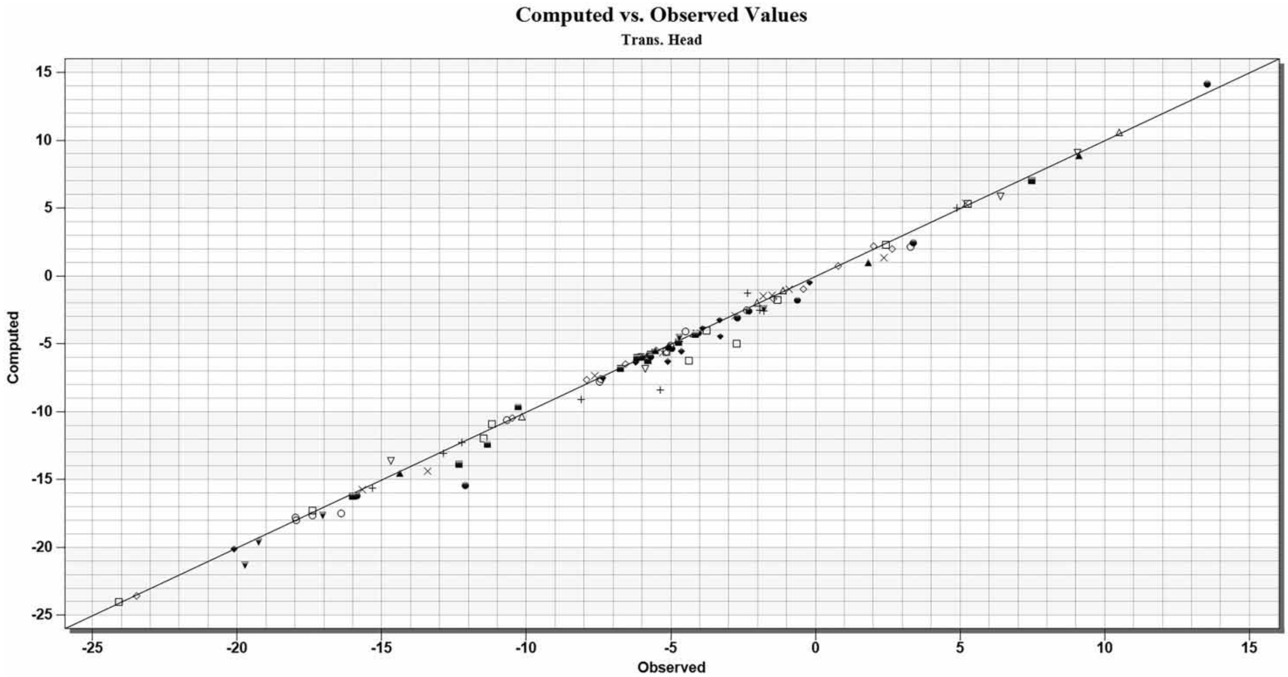

Figure 12 | Comparison of observational and calculated water level in flow model validation.

Table 1 | The amount of model error

Parameter	Steady state (m)	Transient state (m)	Validation (m)
Mean error	0.05	0.56	1.08
Mean absolute error	0.08	1.08	1.76
Root mean squared error	0.09	1.87	2.94

To simulate pollution transfer under the influence of density changes, the SEAWAT numerical model was used in the GMS10.6 software environment. By combining MT3DS and MODFLOW, we will have SEAWAT. Figure 16 shows the geometry of the model and the boundary conditions of the model.

To investigate the penetration of contaminated water into the aquifer for the entire study area and during the study period, circles on the entire coastline of the study area in the CHD band (sea border) were defined. Boundaries with a certain seawater salinity concentration (Figure 17) were monitored according to the GMS software outputs to determine if they would have an impact in the study area. If the initial salinity level for fresh water was below 0.5, which was considered to be about 0.3, analysis was started.

According to the output of the model that we see in Figure 10, in most cases the water flows from the coast to the sea due to the existing slope as well as rainfall sources and other factors mentioned; however, in most areas, the water returns during certain seasons and enters the water sources and pollutes the underground water. The highest amount of this return is denoted by the points shown in Figure 10. The easternmost point of Babolsar city, as well as the east of Amirabad port and the Miankale area had the highest amount of erosion and changes in the coastline. In some central points of the target range, such a return can be seen in different seasons, which is less than the mentioned areas.

In the following, according to the output of the analysis in the GMS software in different months, we will analyze the amount of salinity infiltration at different parts of the aquifer.

Over 28 months (from October 2016 to February 2019), weekly time steps in the GMS software analyzed the amount of changes in the coastal areas where intrusion takes place based on the outputs (Figures 18–22). In the current study, stable

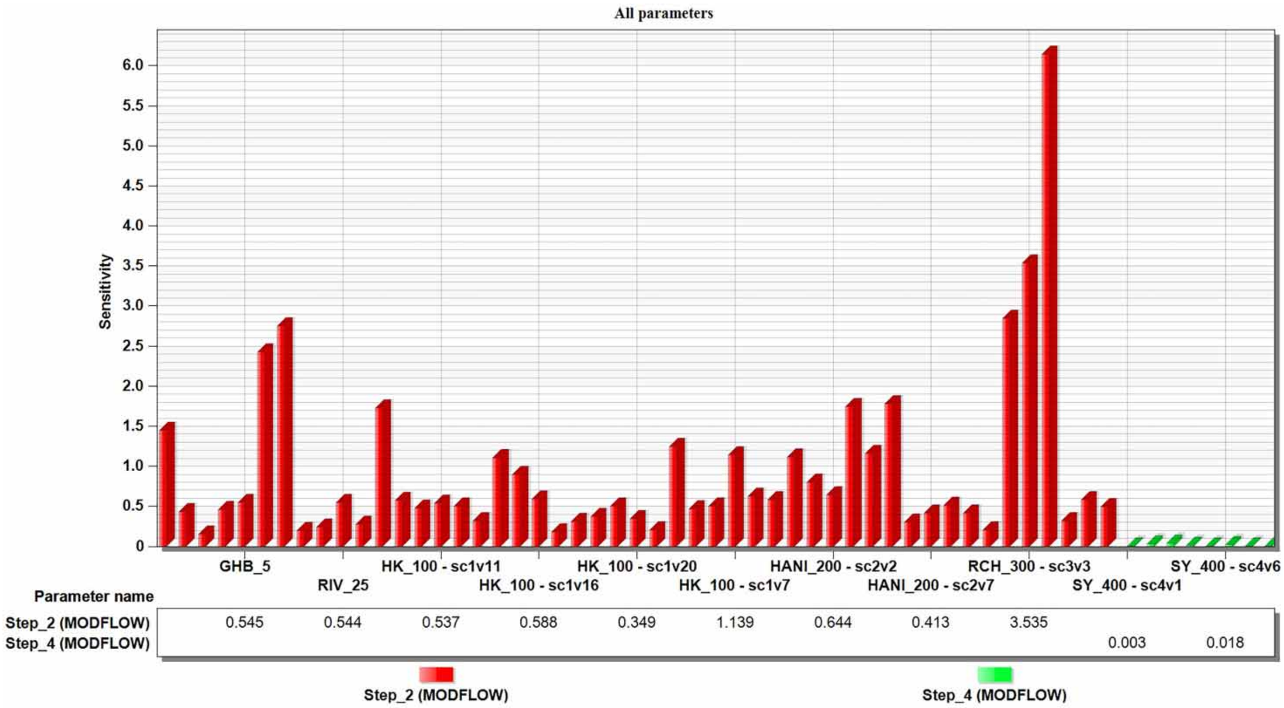

Figure 13 | The results of the sensitivity analysis of the available data.

conditions are considered for October 2016. According to the output of the software for the first month, as seen in Figure 18, at the beginning, that is, during October 2016, the conditions with the same initial amount of return pollution will be the minimum amount. With 149 exits for 28 months, that is, almost every week, we examined the target area in terms of pollution. The amount of salinity in the first output of the software in October 2016 was less than 0.5 ppt. Over 1 year until October 2017, according to the output in Figure 20, the amount of this salinity reached 60 ppt, which shows that the amount of salinity in some areas increased 120 times over 1 year. The results show that the amount of pollution increased and reached its peak in October 2017 (Figure 20). One of the most important factors of this pollution increase was the changes in the level of the Caspian Sea due to the increase in water entering the sea in the spring and summer seasons. This increase in the water level is caused by the climatic changes of the Volga water basin in the north of the Caspian Sea. As can be seen in the different outputs, the amount of pollution sometimes decreases and increases again, which changed based on the changes in the sea level, the feeding rate of the aquifer, and different infiltration and feeding conditions. It is noteworthy to examine the areas where there is the greatest amount of pollution penetration. According to the results of 149 outputs, the highest amount of contamination from the eastern part of Babolsar and also the easternmost part of Amirabad port was the Miankale area. In the middle areas of the study area, the amount of infiltration was constant and was based on the initial salinity value. Given the considered wells, we did not have much influence in these areas. It should be noted that during the entire study period, the eastern and western areas of the aquifer had a very large influence and it was stable in some months and then the increasing trend repeated.

We will discuss why the largest amount of salinity and sea pollution transfer to the underground water table is in the west and east of the study area.

3.2. Research findings

3.2.1. Caspian Sea volatility prediction

According to water level prediction models based on the fluctuating behavior of the Caspian Sea and information from its century-old stations, the water level has been increasing since 2017. The results of these studies are included in the bulletin (CASPCOM), the results of six prediction models of the Caspian sea tidal behavior using long-term data of four leveling stations (given time series): Makhachkala (1900–2011), Baku (2011–1900), Krasnovodsk (Turkmenbashi) (1900–2011),

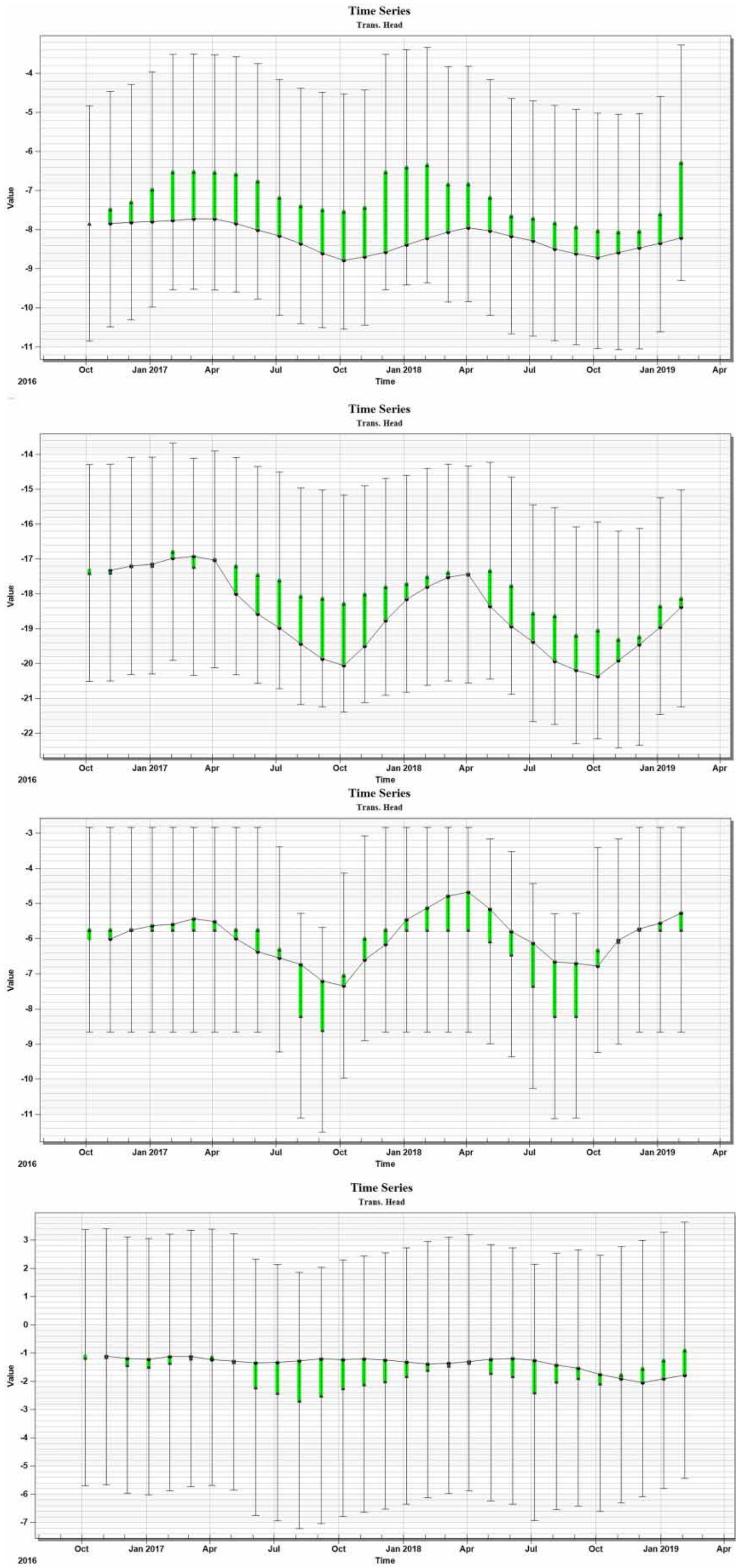

Figure 14 | Calibration error and acceptable error compared to observed and calculated values.

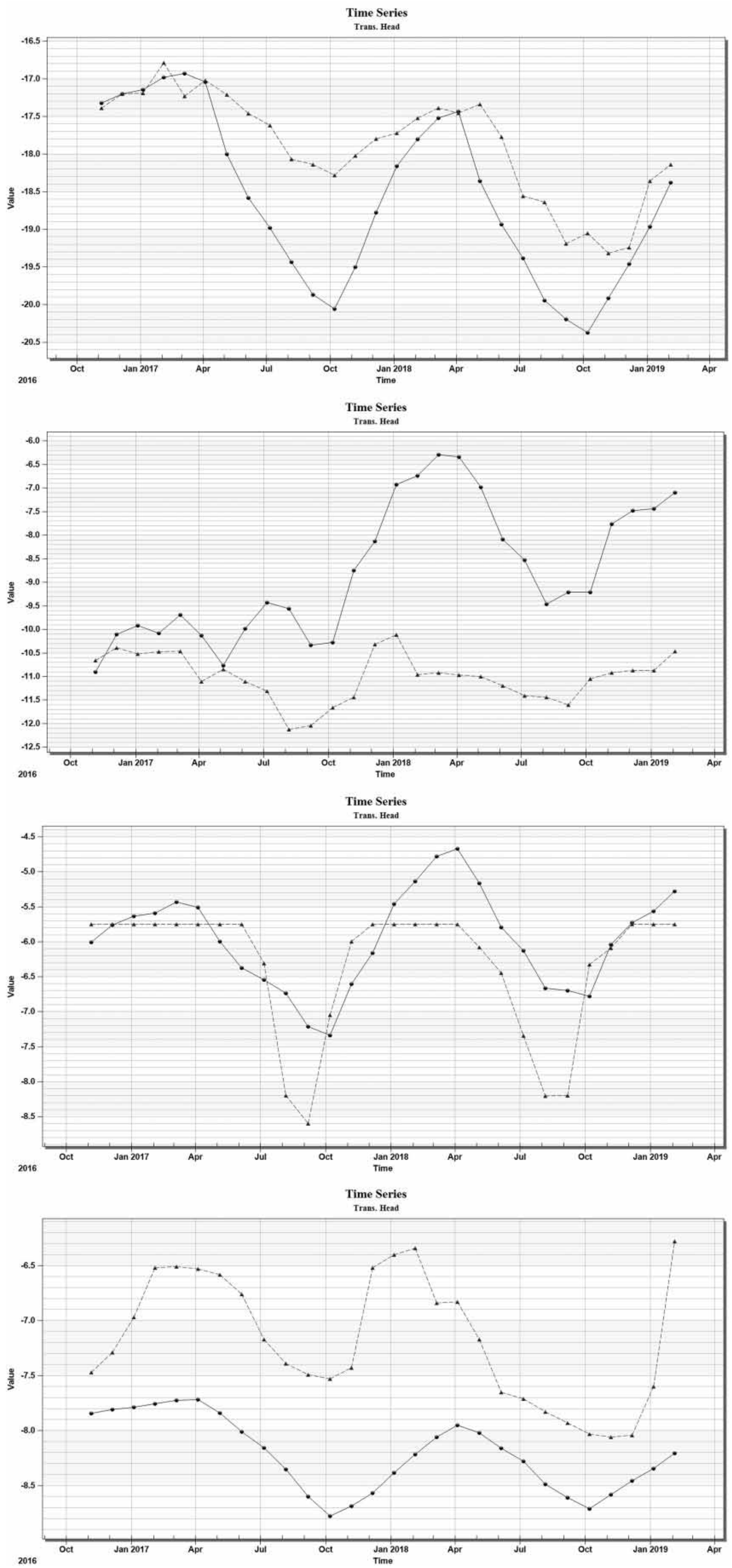

Figure 15 | Observational and calculated water level in four observation wells 30, 36, 48 and 6.

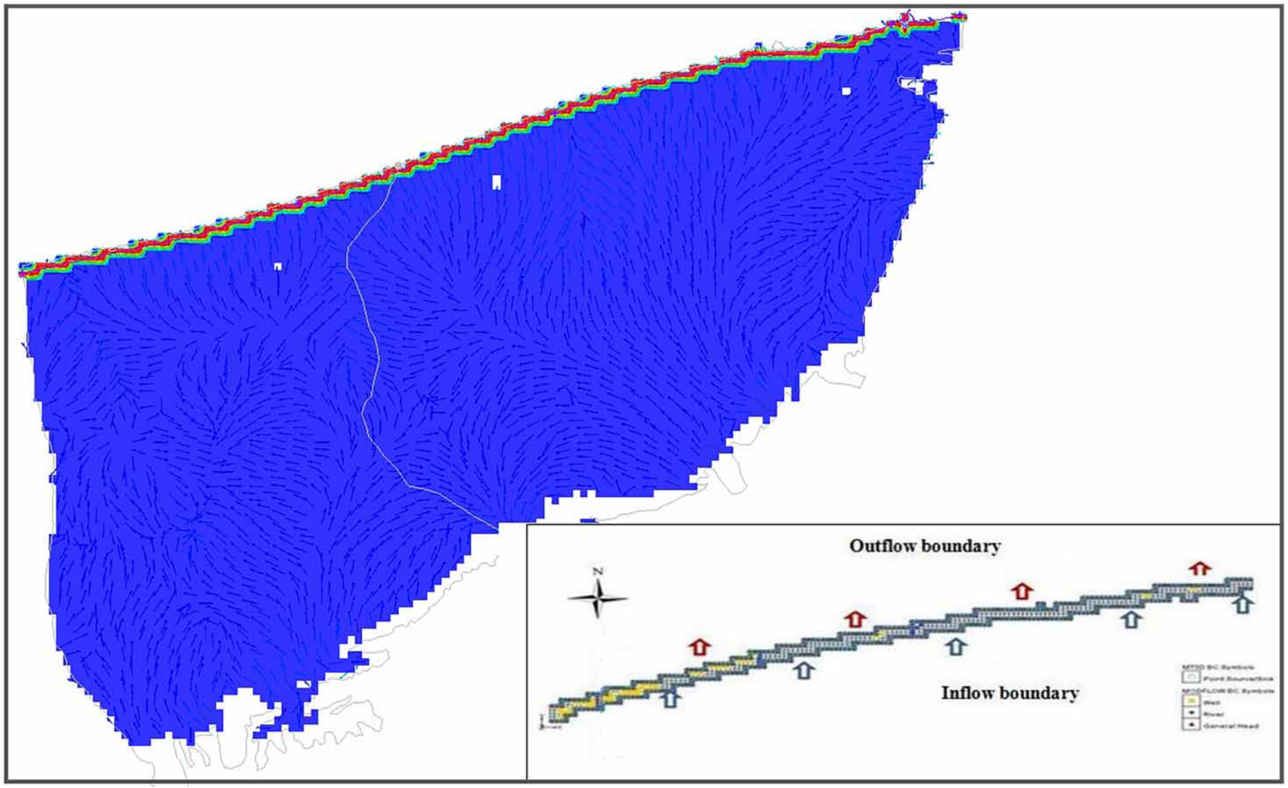

Figure 16 | Geometry and boundary conditions of the model.

Figure 17 | Determining the initial salinity concentration at all points of the coastline of the research area.

and Aktau (1961–2011). Fluctuations will be seen in the flow of the Volga River. The selection criteria of these stations were the length of the available time series, the ability to use the data to estimate the sea water level, and the absence of data.

3.2.2. Causes of water level increase

According to the results of the current analysis, the water level of the Caspian Sea has increased recently and one of the main reasons for the improvement of its water balance is the increase in the flow of the Volga River (which supplies 80% of the water of the Caspian Sea). In 2016, the flow of the Volga River into the Caspian Sea was 261 km^3/year and was 8%

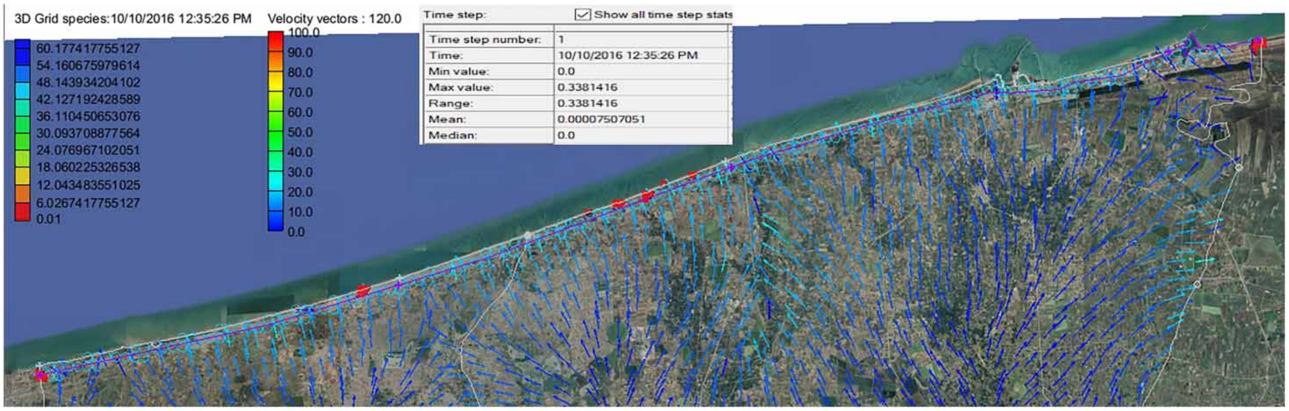

Figure 18 | The output of the software for October 2016.

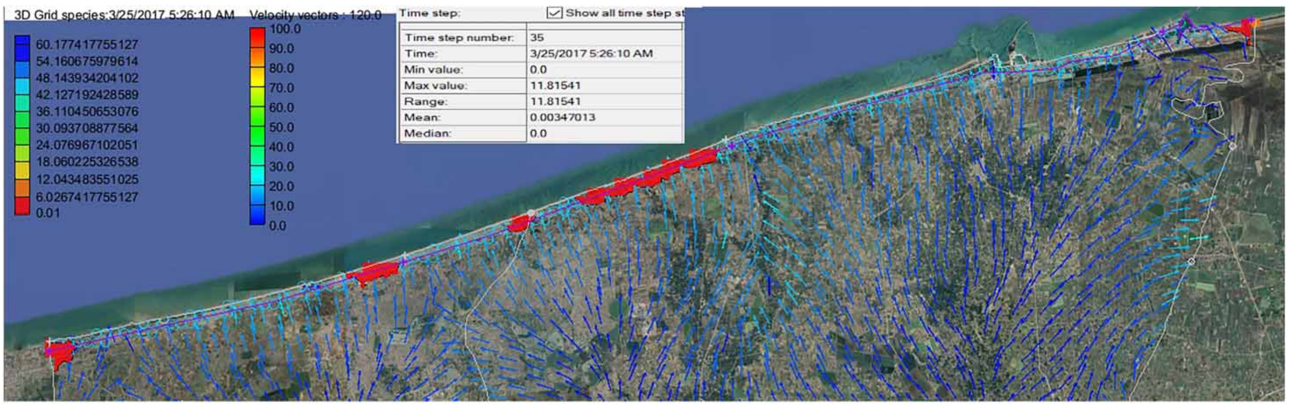

Figure 19 | The output of the software for March 2017.

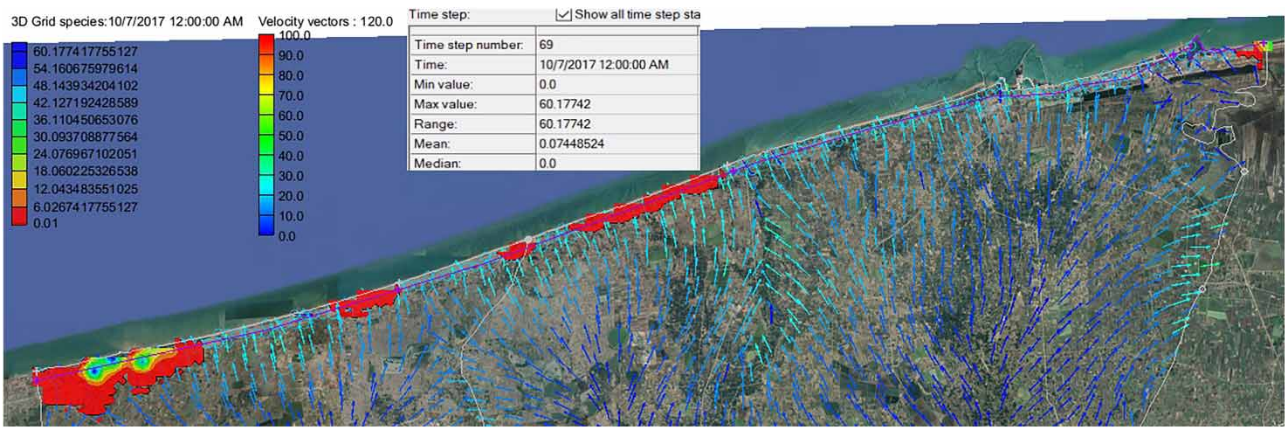

Figure 20 | The output of the software for October 2017.

higher than its normal water level. The recent increase in the water level was not related to the natural ups and downs of the sea; however, of the increase in the water level could possibly be a result of a new fluctuating cycle of the Caspian Sea, which is also mentioned in the forecasts.

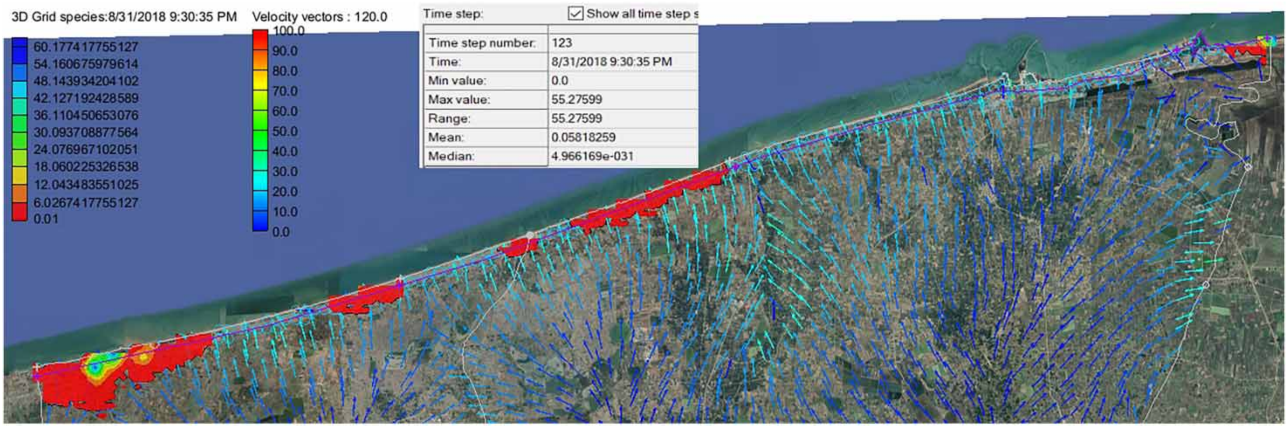

Figure 21 | The output of the software for August 2018.

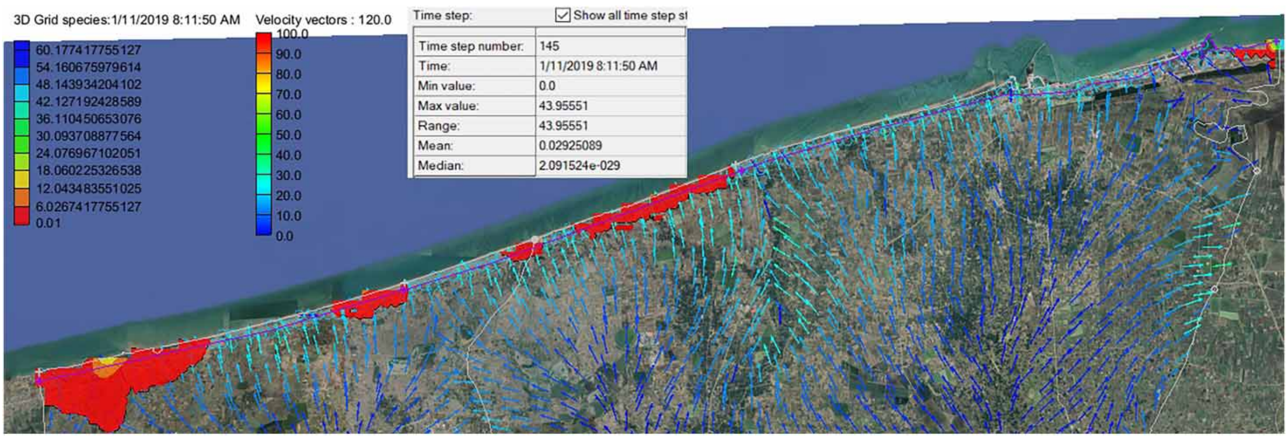

Figure 22 | The output of the software for January 2019.

Changes in the coastlines due to increasing water levels in the Caspian Sea since 2017 can cause increasing pollution. This is discussed next. The aquifer is one of the most eroded parts of the studied area, and the increase in water level and changes in the coastline will have the greatest impact on these parts which are more vulnerable. In addition, according to the software outputs, the highest amount of penetration was in October 2017, due to the increase in the sea water level that year and the Volga flooding, which reached its maximum in the summer season. In addition, with the influx of pollution into the aquifer, we studied its direct connection with climate change and sea level changes. During the last months of the year, as the Volga water level decreased, the rise in the sea level rate also decreased and then remained constant. The amount of pollution penetration into the aquifer also remained constant and did not increase significantly. This process is the same for the following years of the study. Considering the location of the coastline from the beginning of Babolsar to Amirabad port, we analyzed the changes of its coastline. In the Amirabad port region, in the western part of the coastal structures built in the study area, the dominant phenomenon is sedimentation, and in the eastern part, the phenomenon of erosion is striking. The findings show that with the prolongation and advancement of these structures in the sea, the aforementioned processes have become more intense and in such a way that the greatest amount of sedimentation in the studied area is in the western part of Amirabad port, and the greatest amount of erosion is in the eastern part of this port and it seems that this process will continue. It is worth mentioning that the amount of movement and significant changes that have occurred in the coastline as well as the growing process of sedimentation during a short period of time in the region shows the importance of the need to continuously monitor the changes and movement of the coastline in the northern parts of the country. It also emphasizes efficient exploitation and management of beaches. At the end of the study area in the Bahnmir-Babolsar region, according to the studies conducted (Kordavani 2014), it can be seen that due to the interference of the social environment with the beaches and many constructions, as well as the changes in the water level in the past years had the highest amount of beach erosion in the target area, and an example is shown in the the figure below (Figures 23).

As can be seen from the figure, a 100-m intrusion of the coastline can be seen in the east of Babolsar. In this part, we have the highest amount of beach erosion due to the increase in sea level, as well as the slope of the area and the changes caused by the existing constructions on the coastline. Due to the increase in the water level since 2017, the amount of erosion in this area will also increase. These changes and erosion for the middle areas of the researched area are much less than its eastern and western areas (Azam 2020). As can be seen in Figures 24 and 25, the highest amount of contamination to the underground water table is from the westernmost area of the target range, i.e., the beginning of Babolsar and also the easternmost area of the range, i.e., Amirabad port-Miankale. According to the studies done on the changes in the coastline, the highest amount of erosion and thus the changes of the coastline have been observed in this area. The increase in sea levels during the research period and the increasing influx of contaminated water into the aquifer from areas with the most erosion increased the vulnerability of the Caspian Sea coastal aquifer. In past studies, the effects of various factors on the pollution of the Caspian Sea coastal aquifer, including changes in the coastline and changes in sea level, have not been mentioned at the same time. But in this research, we found a direct relationship between the level of pollution of the aquifer and the changes in the coastlines of the studied area. Further research and investigation of this issue is very important to preserve fresh water resources for future generations.

Figure 23 | The advancement of the coastline in the east of Babolsar.

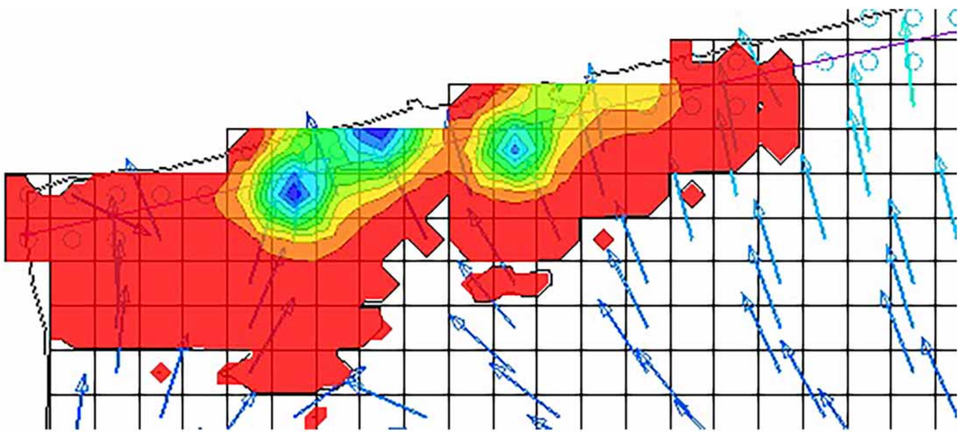

Figure 24 | The westernmost part of the aquifer area.

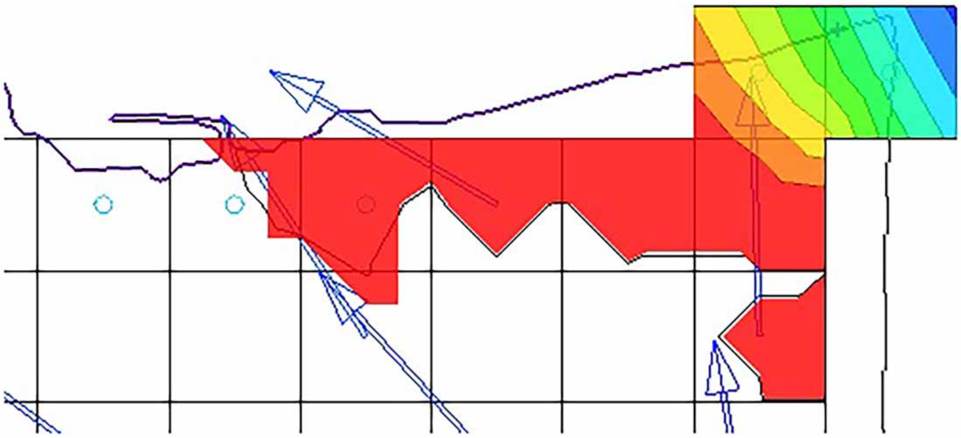

Figure 25 | The easternmost part of the aquifer area.

4. CONCLUSIONS

In this article, GMS software was used to investigate the vulnerability of the northern coasts of Iran due to the effects of climate change on the sea level and the changes in the coastline during a 3-year period (October 2016 to February 2019). The aquifer was simulated using MODFLOW and MT3DMS numerical models for underground water flow and salinity transfer. After the construction and implementation of the groundwater flow model, the qualitative aquifer model for simulating the salinity transfer using the default initial concentration of salinity and using the MT3DMS model in the same simulation period of the groundwater flow model (28 months with a weekly time step in 149 cases) was prepared, and after that the parameters affecting dispersion were recalibrated. The quantitative and qualitative model results show the high accuracy of the simulated model. Next, to investigate the intrusion of the salt water front into the Behshahr-Babolsar plain aquifer, a general survey of the studied plain was done using the SEAWAT model. The model built in the soft environment of SEAWAT was used to predict the progress of salt water over 3 years, assuming the continuation of the current trend in feeding and draining the aquifer. There has been an increase in the salt water advance for the eastern parts, i.e., the area of Amirabad port, and the western parts, i.e., the beginning of the city of Babolsar. For a better integrated management of underground water, a conceptual model was used to simulate the movement of salinity in the aquifer of the study area. To create a conceptual model, images were first drawn in GIS and then zoned in GMS. According to results from 112 observation wells in the study area and about 35,000 pumping wells, the very good compliance of the observed-calculated water level values indicates the high accuracy of the model. By comparing the value of the underground water level, the ability of the model to predict the location of the underground water level in the period of different stresses was evaluated and confirmed. Also, by comparing the error value of the underground water level calculated by the model and the observed underground water level, the ability of the model to evaluate each of the observation wells was been determined. The value of the root mean squared error of the model for the calibration period of the transient state is 1/87 m, which is much lower for the steady state, according to the number of observation and pumping wells. According to the results, the model was able to correctly simulate the conditions of the aquifer. With the validation of the model, the accuracy of the calculation algorithms used to solve the verification equations and the computer code performed well.

A conceptual model including a flow simulation scenario was considered to determine the amount of salt water advances due to the combined effect of climate change on the increase in sea water level and changes in the coastline and changes in the feeding rate. The results of the study are classified as follows:

1. The results of the investigation for 28 months from the beginning of the study to observe the level of vulnerability of seawater intrusion into the aquifer and its pollution show that, according to the initial salinity concentration in parts of the aquifer, the amount of pollution increased every month and the increasing trend during the study period is quite evident. The amount of this salinity ranged from 0.5 to 60 ppt, which shows that the amount of salinity in some areas increased 120 times in 1 year. It should be noted that based on different conditions such as aquifer feeding and sea water return rate to

the aquifer based on the seasonal rise and fall of the sea level, the infiltration of polluted water sometimes decreased and remained constant, but the trend of increasing infiltration of contaminated water into the aquifer during the study period is quite tangible.

2. The highest amount of contamination in the aquifer area was from the western area of the aquifer, i.e., Behnmir-Babolsar area, and the eastern area of the aquifer, i.e., the amirabad port-Miankala area. The level of infiltration in these two areas showed an increasing trend during the study period. In the middle parts of area, a constant amount of infiltration was seen, and the volume of input to the aquifer did not increase in different seasons like in the eastern and western regions.
3. Based on the surveys done on the coastline, the highest amount of beach erosion was observed in Babolsar and Bandar Amirabad-Miankalah, and the changes in the coastline in this area are very significant, unlike the middle parts of the area. The middle areas of the studied area were mainly sedimentary.
4. During the study time period, based on water level prediction models which are based on the fluctuating behavior of the Caspian Sea and the information of its century-old stations, the water level of the Caspian Sea will increase from 2017. According to the level of pollution influx from the eastern and western parts of the studied area, we obtained a direct relationship between climate changes and the increase in the Caspian water level, and also between the changes in the coastlines in the researched areas and the excessive extraction of underground water resources, which caused an increase in the amount of erosion and the penetration of pollution into the relevant aquifer.
5. Considering that there have been changes in the coastline in the entire studied area, in places of erosion, the influx of sea water or polluted water into the aquifer was very high. There was a salinity increase of up to 60 ppt, which is much higher than the minimum seawater salinity of 2 ppt. It should be noted that the inflow of salt water is much less in some places where sedimentation and drying of the sea have occurred.
6. The sensitivity analysis of the characteristics of the aquifer shows that the return flow, rivers, hydraulic conductivity, permeable boundaries, and specific yield are more effective than other factors.

Also, the prediction results of the model indicate that with the continuation of the current trend of the aquifer and no change in the current prevailing conditions, i.e., the increase in erosion in the region and regardless of the increase or decrease in the extraction from the aquifer, there is a possibility that the balance of salty and fresh water will be disturbed and salty water will move further toward the underground water table. The results obtained from the invasion of sea salt water fronts toward the aquifer show that this topic is in accordance with the studies of other researchers. Climate change and changes in coastlines have had a great impact on increasing the advances of saltwater fronts. The results of this study are equal to the results of Ketabchi *et al.* (2014a) who used a SUTRA (saturated–unsaturated transport) numerical model to investigate the effects of climate change on the rate of saltwater advance in steep coastal aquifers. The results show that the combined effect of the sea level rise and the changes in the coastline cause the intensification of the advances of salt water. Stein *et al.* (2019) investigated the role of saltwater and freshwater invasion and interphase and reached similar results. The results show that the drilling of unauthorized wells and the arbitrary harvesting of water wells is one of the most important factors that threaten the underground fresh water resources of the desired plain, cause the drop of the underground water level, and increase the penetration of pollution. Considering that with the development of salt water in the coastal aquifers, the return of salt water is time-consuming and difficult; therefore, management and correct decisions are necessary to prevent the harmful effects of salt water and pollutants destroying the aquifer.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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