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Investigating effects of climate change, urbanization, and sea level changes on groundwater resources in a coastal aquifer: an integrated assessment

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Abstract Urbanization and climate change are causing numerous side effects on groundwater resources. In this study, an integrated modeling approach by linking soil and water application tool (SWAT), modular finite difference groundwater flow (MODFLOW), and three-dimensional variable-density groundwater flow coupled with multi-species solute and heat transport (SEAWAT) models were used to exhibit responses of groundwater systems, in terms of flow and salt concentrations to current and future climatic and anthropogenic changes. Future climate scenarios for periods of 2010–2040 were generated from the Canadian Global Coupled Model (CGCM) for scenarios A1B, B1, and A2 which was downscaled by the Long Ashton Research Station weather generator (LARS-WG) providing precipitation and temperature patterns for the period 2018–2040. The GCM's outputs were applied to SWAT model to estimate recharge rate for the ten scenarios designed to assess the sensitivity of the aquifer to urbanization and climate change. The estimated recharge rate from SWAT was utilized as an input in numerical groundwater model to evaluate saltwater intrusion (SWI), changes in freshwater storage within the aquifer system, and changes in groundwater level. Based on the results of each scenario's simulation, increase of pumping rate yield by future population growth will have more adverse effects on the unconfined aquifer. The derived information from this study can be used to improve future works by developing a better understanding of the managed and unmanaged response of freshwater storage and unconfined groundwater systems to climate change and anthropogenic activities.

Keywords Saltwater intrusion · Coastal area · Climate change · Urbanization · Groundwater resources · Anthropogenic impacts · SWAT · MODFLOW · SEAWAT · Recharge

Introduction

Over recent decades, anthropological activities have yielded dire consequences on the environment. Our activities lead to a sharp increase in water demand and reduced recharge rate of groundwater resources. Population growth, urbanization, and climate change are prominent reasons of some serious problems for water resources. Coastal aquifers are at greater risk of contamination from saltwater intrusion (SWI) processes (Dokou and Karatzas 2012). The spread of SWI is highly dependent on the level of freshwater in the aquifer. The interface can move toward the sea, if levels of water raise in the freshwater part of the aquifer. Moreover, the interface may move inland which can lead to a possible risk or threat to fields of well (Dausman and Langevin 2005). The effects of worldwide developments are more severe in coastal zones, where population densities are higher and landscape and oceanic alteration act in combination. Based on the rise of coastal megacities, mass tourism,

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fisheries, land reclamation, drainage, coastline protection, and agricultural activities which are increasing in an upward trend in last decades, coastal landscapes have become unrecognizable and changed in a concerning trend (Post and Werner 2017). Sometimes the increased temperature caused by climate change would affect evapotranspiration, soil moisture, and precipitation patterns. One of the main reasons of increase in rate of precipitation is increase in temperature; it may cause changes in amount of rainfall or precipitation at the local scale, depending on the climatic conditions and topography (Ranjan et al. 2006).

Some researchers and explorer have been using modeling studies to predict the vulnerability of water resources of groundwater due to the future scenarios (Masterson and Garabedian 2007; Oude Essink et al. 2010; Praveena and Aris 2010; Ranjan et al. 2006; Rozell and Wong 2010; Sherif and Singh 1999; Sulzbacher et al. 2012; Chang et al. 2016; Yu 2010; Kamali and Niksokhan 2017). Abbaspour et al. (2009) use SWAT model to create a hydrological model and calibrated it from 1980 to 2002. Future climate scenarios were generated from the three scenarios of Canadian Global Coupled Model (CGCM) model which were downscaled. The hydrologic model was then utilized to investigate the effect of future climate on precipitation, blue and green water, and wheat's yield in Iran. The results of this study illuminated that the wet regions of the country will receive more rainfall while dry regions will receive less. Analysis showed that larger-intensity floods in the wet regions and more prolonged droughts in the dry regions will happen in the future based on the future scenarios. Climatic scenarios generated quite different results in the dry regions of the country at the subbasin, although the results in the wet regions were similar. Moridi et al. (2018) evaluated sustainable management of groundwater in Tehran by coupling simulation and optimization models of cooperative and non-cooperative approaches. Alaviani et al. (2018) simulated aquifer by GMS software to identify an aquifer in Iran and estimate its groundwater balance.

Havril et al. (2017) performed two-dimensional transient numerical model based on climatic prediction at the Tihany Peninsula. Results showed that future climate trends can cause dynamic evolution and dissipation of transient groundwater flow systems, and the characteristic flow system can change. Preservation of associated groundwater-dependent ecosystems would be challenging under these conditions since long-term climate change could potentially have serious consequences, including wetland disappearance. Rozell and Wong (2010) investigated the effects of climate change on Shelter Island, New York State (USA), using SEAWAT (Guo and Langevin 2002). Two future climate scenarios were created by using predictions for changes in precipitation and sea level rise over the next century. Based on the scenario consisting of a 15% precipitation increase and 0.18-m sea level rise, a 23-m seaward movement of the freshwater/saltwater interface, a 0.27-m water table rise, and a 3% increase in the freshwater lens volume were observed. In the second scenario, consisting of a 2% precipitation decrease and 0.61-m sea level rise, a 16-m landward movement of the freshwater/saltwater interface, a 0.59 m water table rise, and a 1% increase in lens volume were the main result of this scenario.

Few studies have analyzed the integrated impacts of climate, sea level, and anthropogenic changes on aquifers over a long-term period. Webb and Howard (2011) investigated the effects of sea level rise on the variation of SWI. SEAWAT was used to form two-dimensional SWI models so as to illustrate the impact of sea level rise on the movement or lateral movement of salt water in a coastal aquifer. Hydraulic conductivity, recharge, and porosity affect position of sea water after sea level rise. During sea level rise, systems with a high rate of hydraulic conductivity to recharge and high effective porosity developed a high level of disequilibrium, often many hundreds of meters far from sea water toe positions, and the process of equilibrating took several centuries due to a cease in sea level rise. Also, in systems with opposite condition, just a small degree of disequilibrium was formed and generally became stable within decades following a halt in sea level rise. Dams et al. (2008) considered impacts of changes in land use on recharge of groundwater resources by using modular finite difference groundwater flow (MODFLOW) to perform stochastic variations in four types of land use. Sulzbacher et al. (2012) considered effects of density on an issue of groundwater management utilizing a finite element, density-dependent flow model. Finite element subsurface flow system was used to examine the impact of sea level rise on freshwater lenses of the North Sea Island of Borkum. The scenarios of climate change varied seasonally, although changes in land use were not explored in this study.

The main goal of this study is to investigate the long-term changes in a mountain to coast region. Managing groundwater resources in an overpopulated area with fertile agricultural lands and diversified farming activities requires critical planning. Downscaled outputs of GCM were used to run SWAT model to estimate the recharge rate to analyze the impacts of anthropogenic activities, climate change effects, and Caspian Sea level (CSL) changes. Ten different scenarios were designed to predict changes in the head of groundwater and lateral movement of seawater toward coastal region. The model was also used to predict the changes in volume of the freshwater storage within aquifer system. This study is the first modeling study which analyzed effects of all factors on groundwater resources in a long-term period for future.

Materials and method

As mentioned earlier, the main goal of this study is investigating effects of climate change and urbanization on groundwater resources. Figure 1 illustrates the flowchart of the proposed model. Recharge rate, head of groundwater, lateral movement of seawater toward coastal area, and volume of fresh water based on 10 scenarios designed for the next 20 years were calculated for analyzing effects of climate change and urbanization. SWAT (Arnold et al. 1996), Long Ashton Research Station weather generator (LARS-WG), MODFLOW (Harbaugh et al. 2000), and SEAWAT were used to model the aquifer. First, information was collected from water resources and weathercasting institute of Iran for creating hydrological model of the aquifer in SWAT. Then, the model was calibrated by using SWAT Calibration and Uncertainty Procedures (SWAT-CUP) and Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm; the calculated recharge rate in Arc SWAT was entered to MODFLOW model to create transient and steady-state groundwater quantitative conceptual model for current condition. For analyzing SWI, a transient qualitative conceptual model was created in SEAWAT. Ten scenarios were designed in order to investigate effects of climate change, urbanization, and changes in CSL.

Study area

Nowshahr-Nur aquifer is a coastal area located in north part of Iran near the Caspian Sea (Mazandaran Province that covers about 25168×10^5 m^2) (Fig. 2). The highest elevation in this area is about 3565 m and the lowest point is about −26 m above sea level. The north part of the case study is connected to the Caspian Sea, the middle part contains vast forests and agricultural land, and the south part of this area consists Alborz mountain ranges. Climate in this case study is categorized into two groups of plain moderate climate and mountainous climate. Precipitation and water table aquifer underlying the mountain to the coastal region are two sources of fresh water in this case study. The north part of this region is connected to the Caspian Sea and rivers are sources of irrigation in some parts of the plain connected to the Caspian Sea (Fig. 2). Every year, 60.67% of precipitation turns to evapotranspiration, 30.41% remains as surface water, and 8.83% recharges the aquifer. The aquifer consists of a 30-m-thick water table in western part of the area, which is composed of coarse grain sand with a layer of clay at the base. By moving from west to east, thickness of aquifer fluctuates between 50 and 100 m containing coarse to fine sand. High-altitude regions consist coarse grain gravel, and the south part of this case study contains fine grain sand like the north region but the second part has a mixture of clay and sand.

There are 33 observational wells in this area for calculating head of groundwater (Fig. 2) and 6000 pumping wells. Agricultural goals and tourist industry are increasing in an upward trend and a wide range of investors are clearing forests and destroying bank of rivers causing some side effects on the environment and natural resources of this area.

Modeling

Watershed simulation: using SWAT for recharge rate calculation

For modeling aquifer groundwater resources, recharge rate was computed by using SWAT (Neitsch et al. 2011) that is a catchment simulation model widely used for assessing the effects of land- management methods and climate. The model requires climate data, land use and land cover (LU/LC) of the study area, topology, soil classification, and topography. LU/LC and soil classification data were derived from the database of Iran geology institute. A 10-m digital elevation model was downloaded from the United States Geological Survey (USGS), used to specify the watershed and to compute

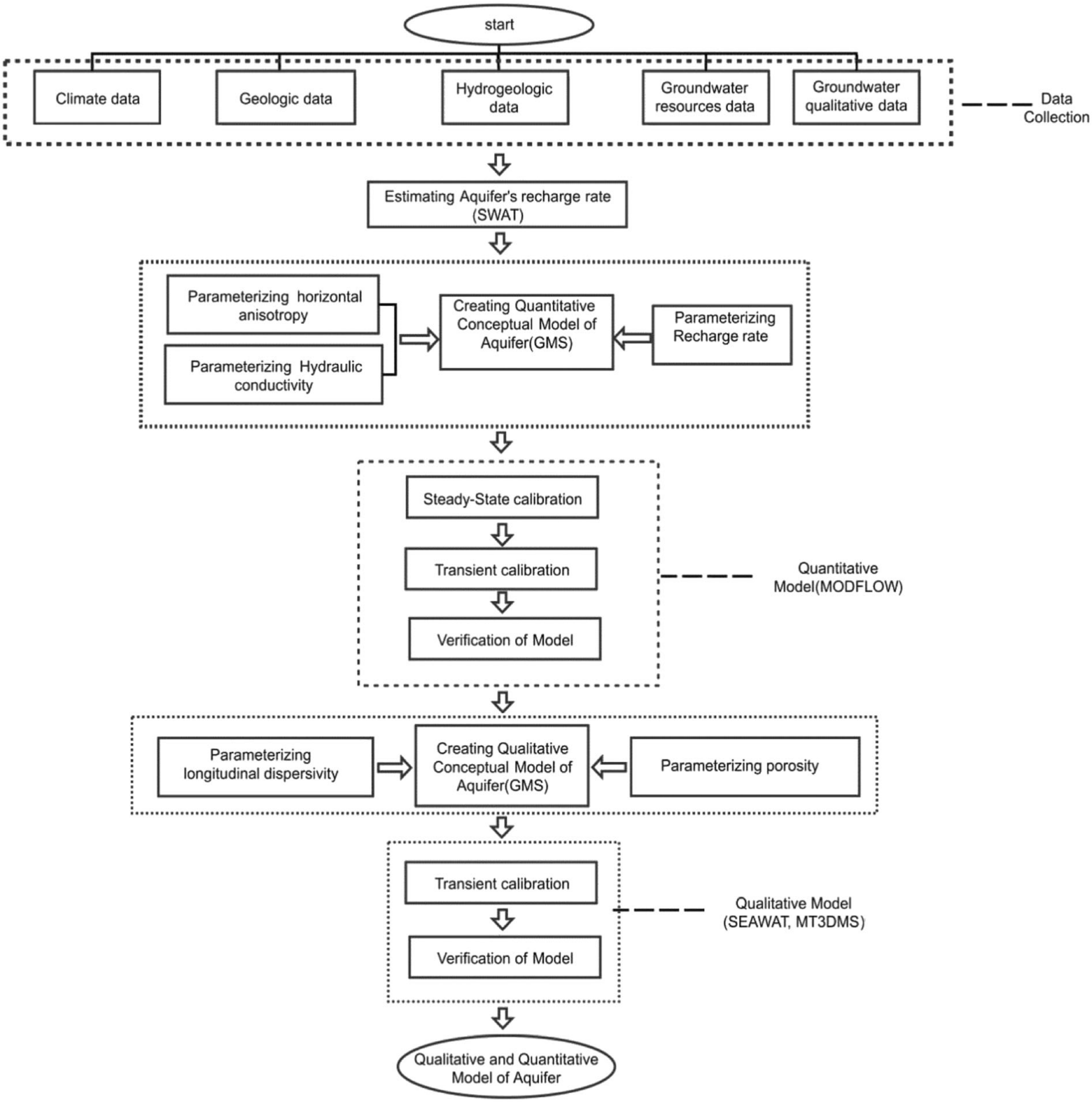
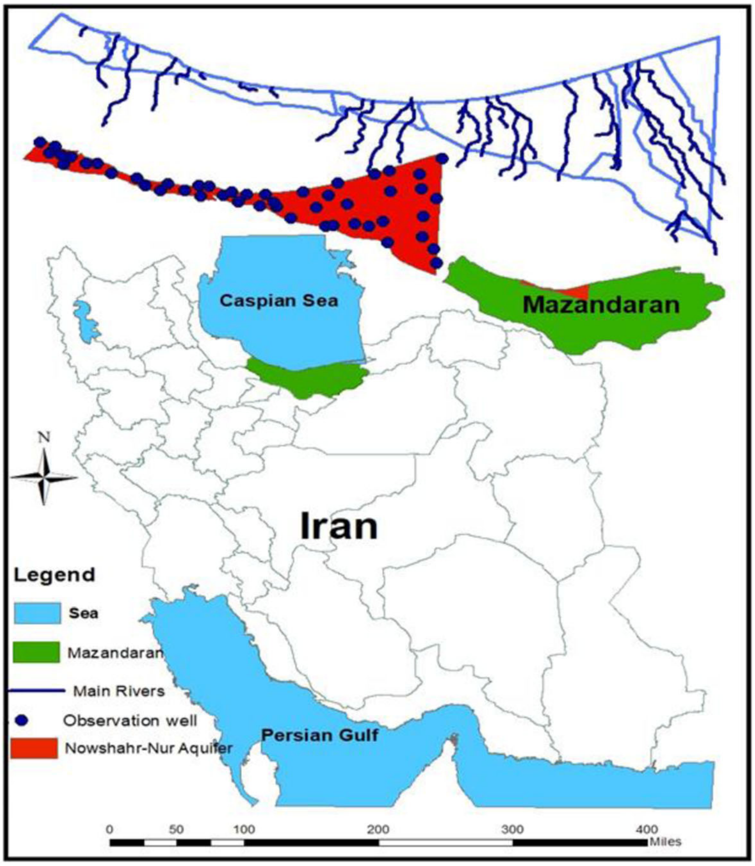


Fig. 1 The flowchart of the proposed methodology

the other topographic parameters. Climate data were obtained from the Iran weathercasting institute, using two synoptic stations' data located in the case study. The Arc SWAT model created 65 subbasins and 234 HRUs. The model has been calibrated and verified with uncertainty analysis using SUFI-2 based on measured daily discharge data from eight hydrometric stations. The calibration (coefficient of determination $(R^2) = 0.83$, Nash-Sutcliffe efficiency $(\mathrm{NSE}) = 0.77$), and verification ($R^2 = 0.70$, $\mathrm{NSE} = 0.70$) results were quite satisfactory for the outlet of watershed. The calibrated SWAT model was used to predict recharge rate from 2018 to 2040 based on future precipitation and temperature. For predicting precipitation and temperature, three widely used scenarios were utilized, A_1B, B_1, and A_2, from the CGCM. Outputs from the CGCM were downscaled by using LARS.

Fig. 2 Map of Nur-Nowshar aquifer (location in the Mazandaran Province and Iran)



Groundwater quantitative three-dimensional modeling: MODFLOW

MODFLOW (Harbaugh et al. 2000) was applied in this study for modeling aquifer's groundwater. Two steady-state and transient models were conducted as groundwater model. The recharge package of MODFLOW was applied to the model and the calculated recharge rate in SWAT model is utilized for defining this package. The study area is discretized into 177 columns and 69 rows. The eastern and western sides of the model were accepted as no-flow boundaries because there is no hydraulic bond between the aquifer and the neighboring regions; also, the flow lines are parallel to the no-flow boundaries according to the regional flow regime in the study area (Latinopoulos 2003). Because of the straight hydraulic connection between groundwater and seawater in the northern boundary, it was assumed as a constant head boundary (CHB). Eventually, the southern boundary was simulated as a general head boundary (GHB) (Fig. 3). As investigating transport problems is one of the main goals of this study, the northern boundary is very important due to the hydraulic connection with the Caspian Sea which was simulated as a constant concentration boundary (CCB), where concentration was set equal to 11 kg/m^3. RIVER package of MODFLOW was used to simulate the stream–aquifer interaction. Locations and levels of rivers were obtained from an existing GIS shape file created by water institute of Iran. The initial range of parameters before calibration process defined to the model is shown in Table 1. Observation wells' data existing in the case study was obtained from water institute of Iran for simulating head of wells so as to draw a comparison between the simulated head and the observed head of wells. It helps to understand the accuracy of the calibrated model and calculate the head of groundwater resources in the case study. After defining all the necessary data, the model was run in steady-state and transient mode, the transient mode was divided into two processes of validation and verification. The validation period was from January 2002 to

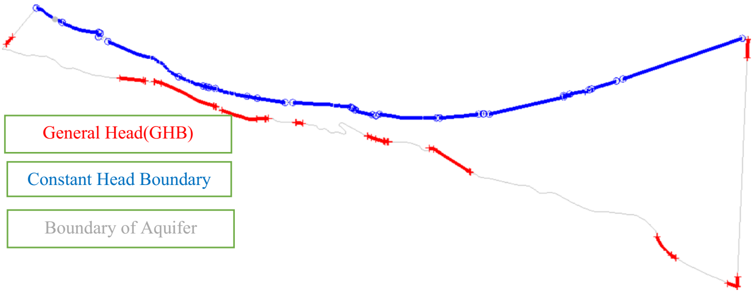


Fig. 3 Map of boundary in Nur-Nowshar aquifer in MODFLOW

December 2014, and the verification started from January 2015 and ended in January of 2016.

Groundwater qualitative three-dimensional modeling: SEAWAT

A wide range of researchers and explorer have utilized SEAWAT as a tool for the simulation process of investigating SWI dynamics (Chang et al. 2011; Chang and Clement 2012, 2013; Masterson and Garabedian 2007; Werner and Simmons 2009). For the identification of SWI and illustration transport of salt water along the Caspian Sea and Nowshahr-Nur coast of Iran, a model was developed. The main part of the area is located along the Caspian Sea which is considered to be the main avenue of transport of saltwater from the coast to the industrial and urban area. For modeling SWI, some parameters like longitudinal dispersivity, porosity, vertical conductivity, specific storage, and starting concentration of salt in coastal areas of the case study were defined to the model. Parameters' value shown in Table 2 was obtained from the database of oceanography institute of Iran. The coast of Caspian Sea covering the study area was taken as a constant concentration boundary with an average total dissolved solids (TDS) of 11 kg/m^3; fluid density was assumed constant. The model was calibrated just for the transient mode for a period of 12 years (since SWI is a slow process) and verified same as MODFLOW model.

Table 1 Model parameters used for MODFLOW

Parameter	Symbol	Value
Hydraulic conductivity	K	0.1–28 (m/day)
Horizontal anisotropy		0–2
Specific yield	S_y	0–0.8

Simulating effects of 10 scenarios of climate change and anthropogenic factors (2018–2040)

Increase in level of sea and reduction of recharge yield by changes in rainfall are the two main climate change-induced hydrological processes that can influence saltwater intrusion in coastal aquifers (Chang and Clement 2012). To investigate impacts of future climate change and urbanization, we designed 10 scenarios based on types of recent changes in the case study, global climate change, and urbanization. All the scenarios were simulated from 2018 to 2040 by running a transient model for this period. For all scenarios, boundary conditions and model parameters were identical to those used in the current condition simulation.

Scenario 1 (base scenario) In the baseline scenario, there are no changes from the present time to the future period from 2018 to 2040 to model the groundwater condition. Parameters like recharge rate and pumping values remained constant in this scenario.

Scenario 2 and 3 (sea level change) Based on a wide range of researches and investigations for predicting level of Caspian Sea, CSL has undergone substantial

Table 2 Model parameters used for SEAWAT modeling

Parameter	Symbol	Value
Specific storage	S_s	0.00001 (m^{-1})
Vertical conductivity	K_z	18 (m/day)
Longitudinal dispersivity	α_L	28 (m)
Porosity	n	0.412
Starting concentration of salt	C_s	11–13 (kg/m^3)
Fresh water density	ρ_f	1000 (mg/m^3)
Salt water density	ρ_s	1024 (mg/m^3)
Reference fluid density	ρ	1000 (mg/m^3)

fluctuations during the past several hundred years (Lebedev and Kostianoy 2005). The causes over the entire historical period are uncertain (Chen et al. 2017). All the predictions for next 100 years of CSL are not reliable, as some of them predicted that this parameter is going to increase in a not too distant future (about + 3 m) and on the opposite line, a group of experts proved that CSL is going to decrease (− 3 m) (Daryaabadi 2010). So head in CHD package of MODFLOW was altered in two different scenarios. Recharge rate and pumping level were held constant like the first scenario.

- Scenario 2: 0.6 m increase in sea level
- Scenario 3: 0.6 m decrease in sea level

Scenario 4 (LU/LC change) This scenario was prepared to investigate the largest possible changes in groundwater resources in response to LU/LC changes. LU/LC alterations affect numerous components of the hydrologic cycle in all aspects (Wang and Kalin 2011). The recently changes in infrastructures and improvement in economic in countries caused negligence to controlling land cover changes. This development caused deforestation, increase in agricultural and industrial activities, destroying bank of rivers for building recreational centers, changes in food productions, and increasing urban areas by replacing orange and rice fields. The scenario is an extreme case which illustrates what would likely be the largest possible change in land cover hypothetically that could possibly occur in the future. The changes in LU/LC in the future are presented in Table 3. In this case, the LU/LC were changed in Arc SWAT model.

Scenario 5 (pumping increase) The fifth scenario simulated increased pumping for the period 2018 to 2040. Rate of pumping in this scenario was increased due to patterns of population growth. The population of Nur-Nowshahr has been steadily increasing over the past 10 years at a rate of 1.5% for each year, so the pumping rates were increased by 1.5%. The recharge rate remains constant like the first three scenarios.

Scenario 6 (dry climate + LU/LC change) This scenario explored the impacts of dry climate change and LU/LC change from the scenario 4. The recharge for this scenario was predicted by SWAT based on the predicted precipitation and temperature by GCM models. To generate future climate scenarios, the CGCM 5.1 was used, and all the generated data were downscaled by LARS-WG for two synoptic stations in the case study. After the process of downscaling, the highest temperature with the lowest precipitation was chosen for calculating recharge rate in a dry climate. The recharge values obtained from SWAT model using the dry climate and land use change predictions were used as the recharge input for the MODFLOW and SEAWAT simulation. Pumping levels were not changed in this scenario.

Scenario 7 (wet climate + LU/LC change) The seventh scenario was same as the sixth scenario, but for estimating recharge rate, instead of using the dry climate change scenario a wet climate change scenario was utilized. The lowest temperature with the highest precipitation was utilized as input data in SWAT model for estimating recharge rate. Pumping levels were held constant.

Table 3 The changes in LU/LC in the future

Land use	Present time percentage in each 10,000 m^2	Changes (%)	Future time percentage in each 10,000 m^2
Peas	5.59	− 0.4	3.5
Urban area with high density	8.37	+ 1.11	14.5
Urban area with medium density	8.78	+ 4.94	22
Water	0.57	0	0.57
Forested area	35.69	− 9.28	22.3
Rice and orange	23.51	− 2.96	15
Other agricultural products	19.12	+ 3.66	22

Scenario 8 (dry climate + LU/LC change + sea level increase) This scenario is a combination of the third and the sixth scenarios. The recharge data as input for MODFLOW model in this scenario equals the recharge rate in the sixth scenario calculated in SWAT for a dry climate. Pumping levels remained same as baseline scenario.

Scenario 9 (dry climate + LU/LC change + sea level decrease) This scenario is a combination of the forth and the sixth scenario. MODFLOW model recharge rate in this scenario equals the recharge rate in the sixth scenario. Pumping levels remained same as baseline scenario.

Scenario 10 (wet climate + LU/LC change + pumping increase) In this scenario, recharge rate calculated in the seventh scenario is exploited as input data for MODFLOW model. Pumping rate is not constant and we use pumping rate of the fifth scenario.

Results

SEAWAT and MT3DMS and MODFLOW transient calibration results

Based on the simulated range by MODFLOW, head of groundwater has decreased from 2002 to 2014. Three of observational wells were chosen to compare model's simulated water level for each well with the observed level reported by water resources institute of Iran. As shown in Fig. 4, the simulated data of observational matched the reported data, although some of the results made errors in predicting highest pick due to some gaps in data's of recharge and other parameters. The green color of calibrated wells illuminates that the total model results reached the general trend well.

The field-observed data also fitted well with the simulated data of SEAWAT model (Zheng and Wang 1999). The simulated concentration levels were also compared with the data available for the salinity observational wells. Change in lateral movement of salt SWI from 2002 to 2014 is not very noticeable due to the low salt concentration of constant boundaries and Caspian Sea. As Fig. 5 shows, majority of the inland monitoring wells were protected from SWI. Salinity in monitoring wells was lower than the seawater concentration. The red color of these wells proves that rate of salinity in the case study is lower than calibrated values, so fresh water is safe from salt water intrusion.

Recharge rate for all scenarios

Figure 6 shows input recharge rate of MODFLOW from 2018 to 2040 calculated by SWAT in all scenarios. Two subbasins were chosen to show changes in recharge rate. The 20-year predictions consist of two different periods. Irregular recharge patterns were the main prediction of climate change during the next 20 years. An average of recharge simulations from 2002 to 2017 was used as the seasonal variations for scenario 1 which is the baseline scenario. Recharge data included in scenario 6 are in the low peak that approach zero in 2018, and recharge in scenario 7 are in high peaks for 2023. Recharge in scenarios 1, 3, 4, and 5 is equal and the calculated recharge for the current time remains constant for these scenarios. Recharge rate calculated in SWAT model for dry climate change is utilized for scenarios 6, 8, and 9. Wet climate recharge is dedicated to scenarios 7 and 10.

MODFLOW results for each scenario

For understanding effects of each scenario on the head of groundwater, three rows of the simulated case study were chosen. Figure 7 shows the location of each row in Nowshahr-Nur aquifer. The prominent reason of choosing three rows from the different parts of the case study is investigating the effects of all scenarios in different elevations of the case study.

The selected rows are as follows:

Row 12: Located near the boundary of the Caspian Sea in the north part of the case study. Figure 8a shows the head of groundwater in each scenario for predicted time series. The model predicted the lowest head for scenario numbers 5 and 10. The highest simulated heads are from scenario 7 modeling wet climate.

Row 26: Located in middle part of the case study and it contains plain regions and agricultural lands. Figure 8b shows the head of groundwater in each scenario for the next 20 years. Again, the simulated head in the fifth scenario is in the lowest peak. Scenario number 10 obtained the highest head in the simulation process, so it has less dire consequences on the head of ground water in the plain regions of the case study.

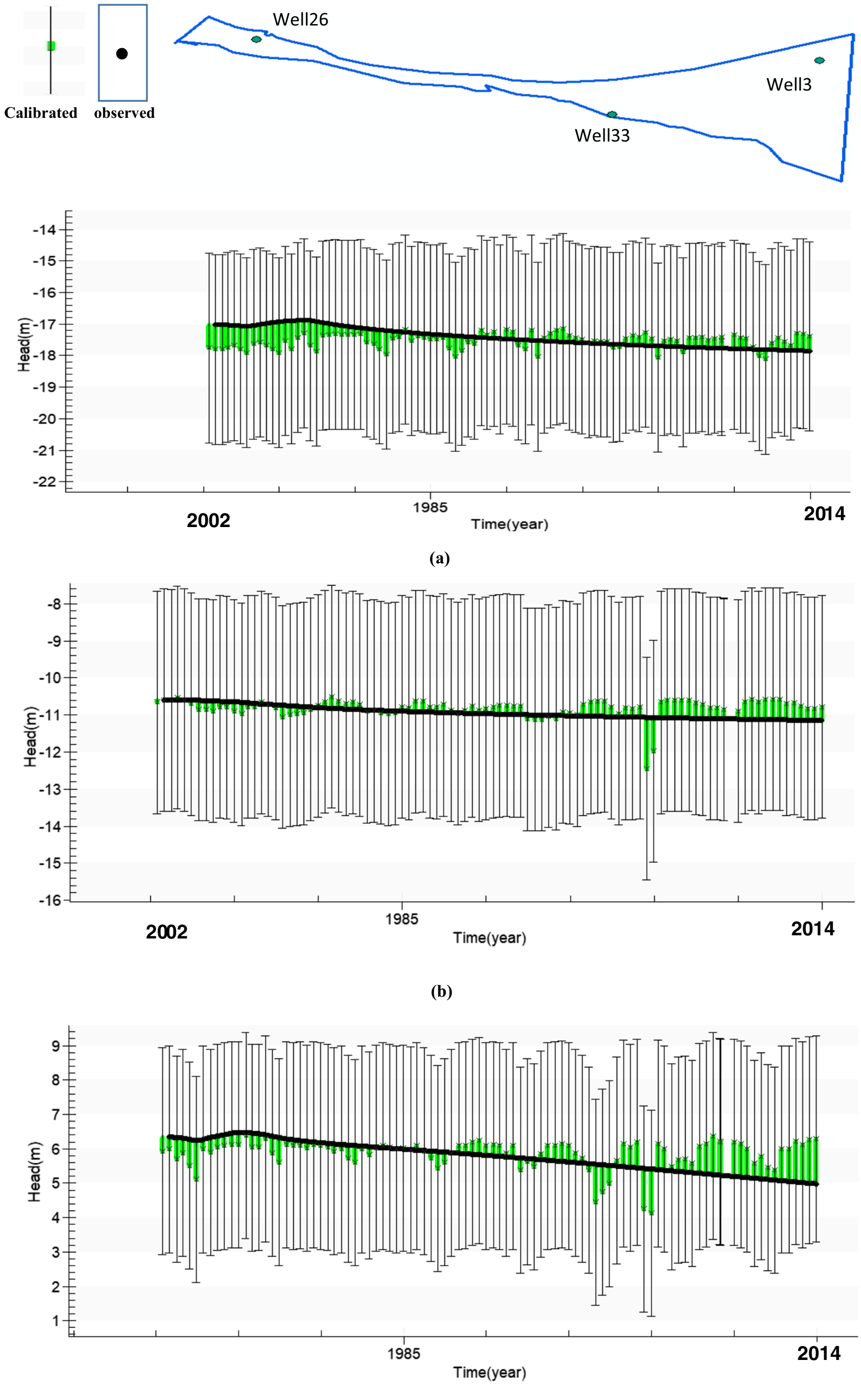
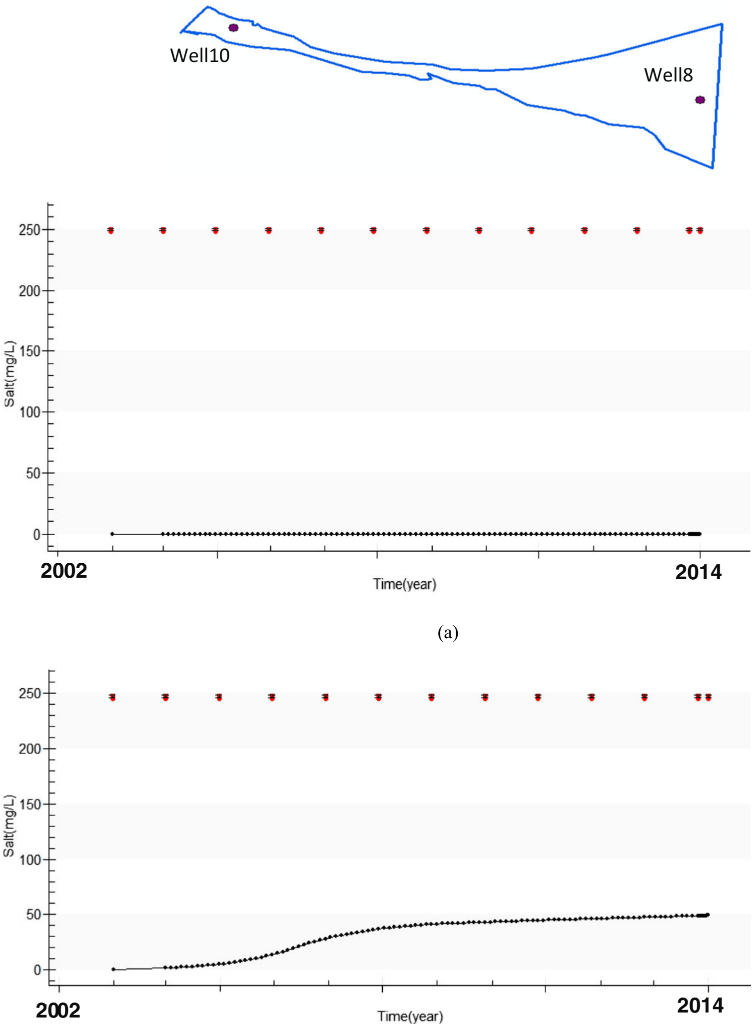


Fig. 4 Simulated and observed hydrographs of water levels in selected wells for 2002–2014 period: **a** well 3, **b** well 26, and **c** well 33

Fig. 5 Simulated values and observed data of salt concentration from selected test wells for 2002–2014: **a** well 8 and **b** well 10



(a)

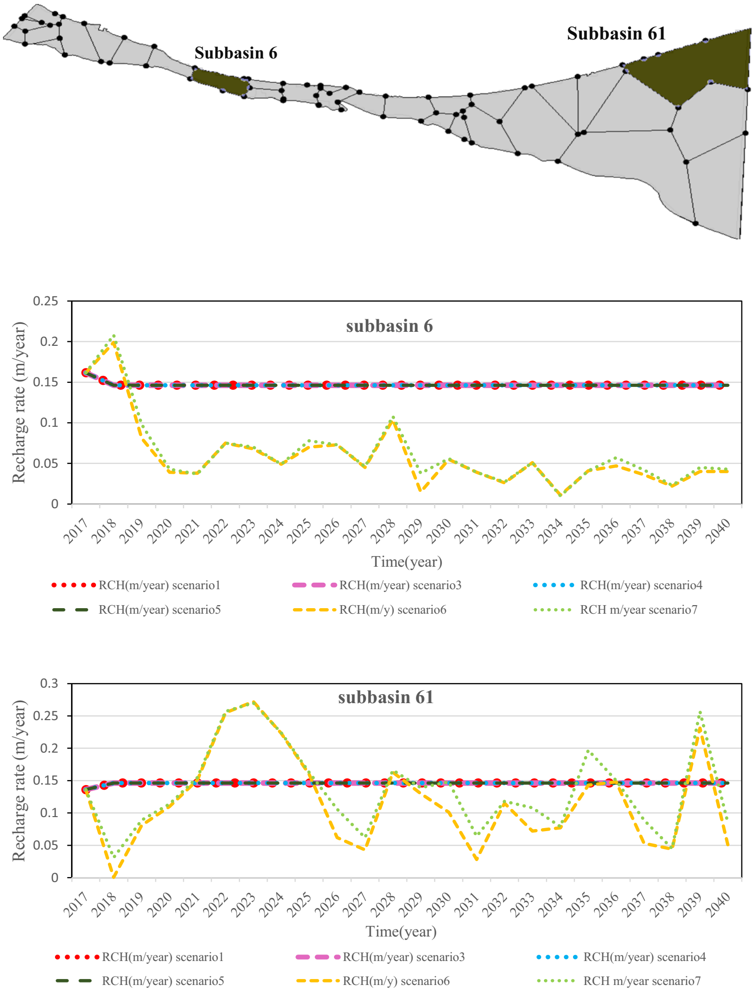
(b)

Row 41: Far from the Caspian Sea and it is located in the high elevation of the case study. Figure 8c shows head of ground water in each scenario. Same as rows 12 and 26, scenario number 5 decreased level of groundwater more than other scenarios even in the south region of the case study. Like row 26, the high peaks are calculated from scenario number 10.

SEAWAT model scenarios' results

Based on the result of SEAWAT model, lateral movement of salt water is not severe in this aquifer for next 20 years. Effects of scenario number 5 are more than those of other scenarios, and other scenarios like 1, 3, 4, 9, and 10 did not show serious changes in lateral movement of salt water toward fresh water. Figure 9a–d illustrates changes in lateral movement of sea water to groundwater; scenarios 5 and 6 were selected for showing the lateral movement of salt water in the case study. In each scenario, the first figure shows the starting day of the simulation and the second figure illustrates the last day of the simulation period. Table 4 indicates salinity ranges from fresh to hyper-saline. Also, by adding color to each boundary in SEAWAT model, changes in each scenario are illustrated in Fig. 9. The blue contours illustrate salt water in the case study, the red contours show

Fig. 6 Input recharge rate of MODFLOW for subbasins 6 and 61



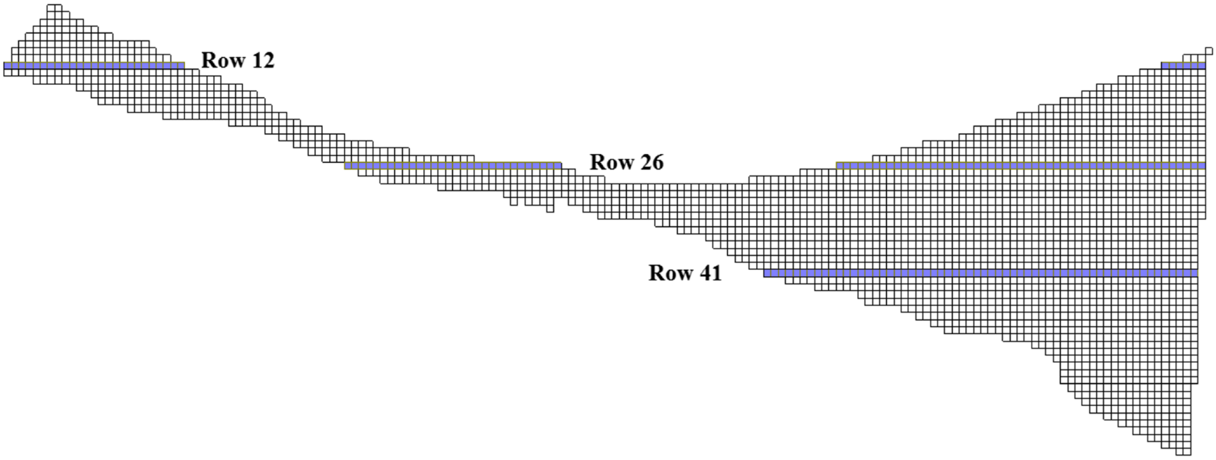


Fig. 7 Location of selected rows in Nowshahr-Nur aquifer

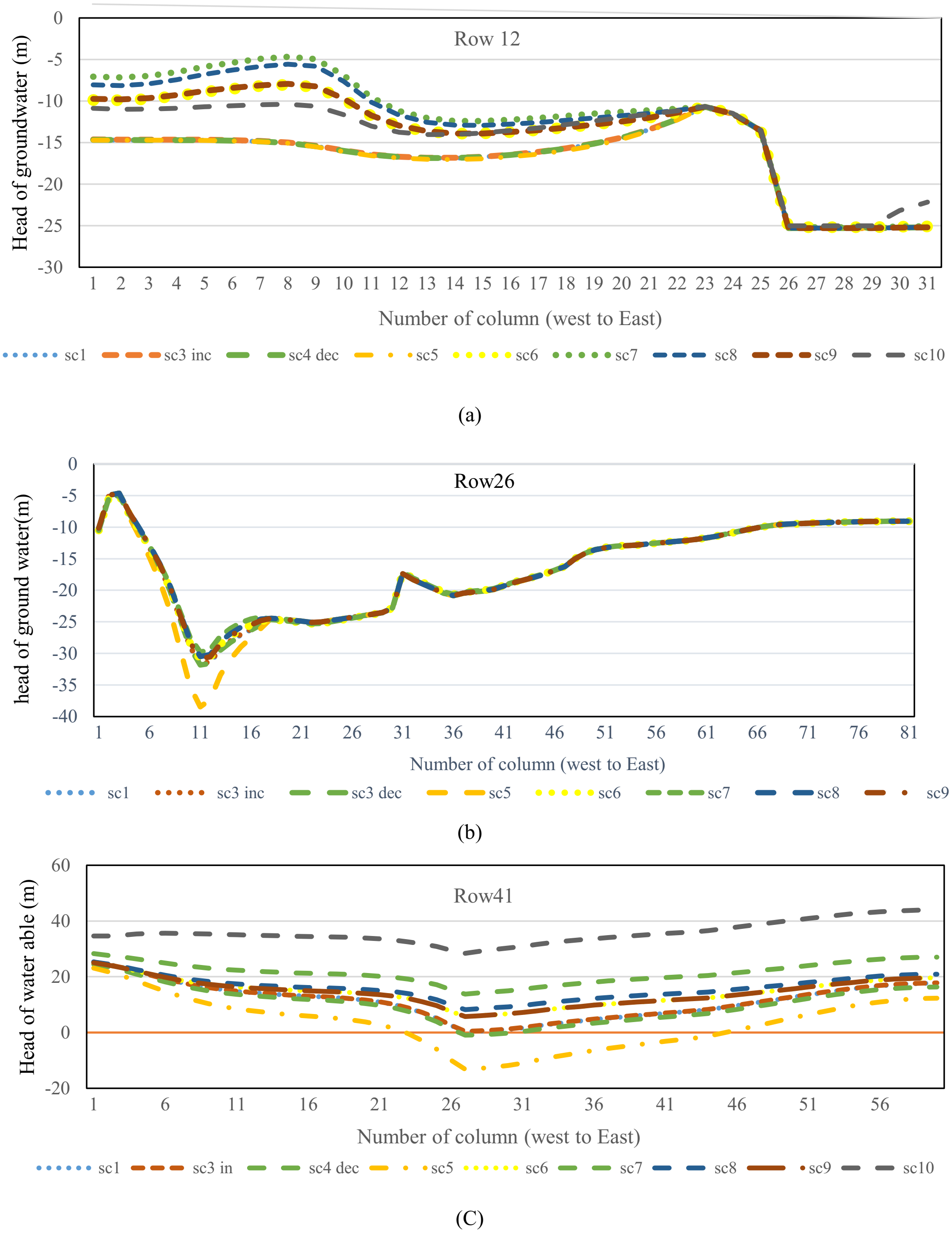
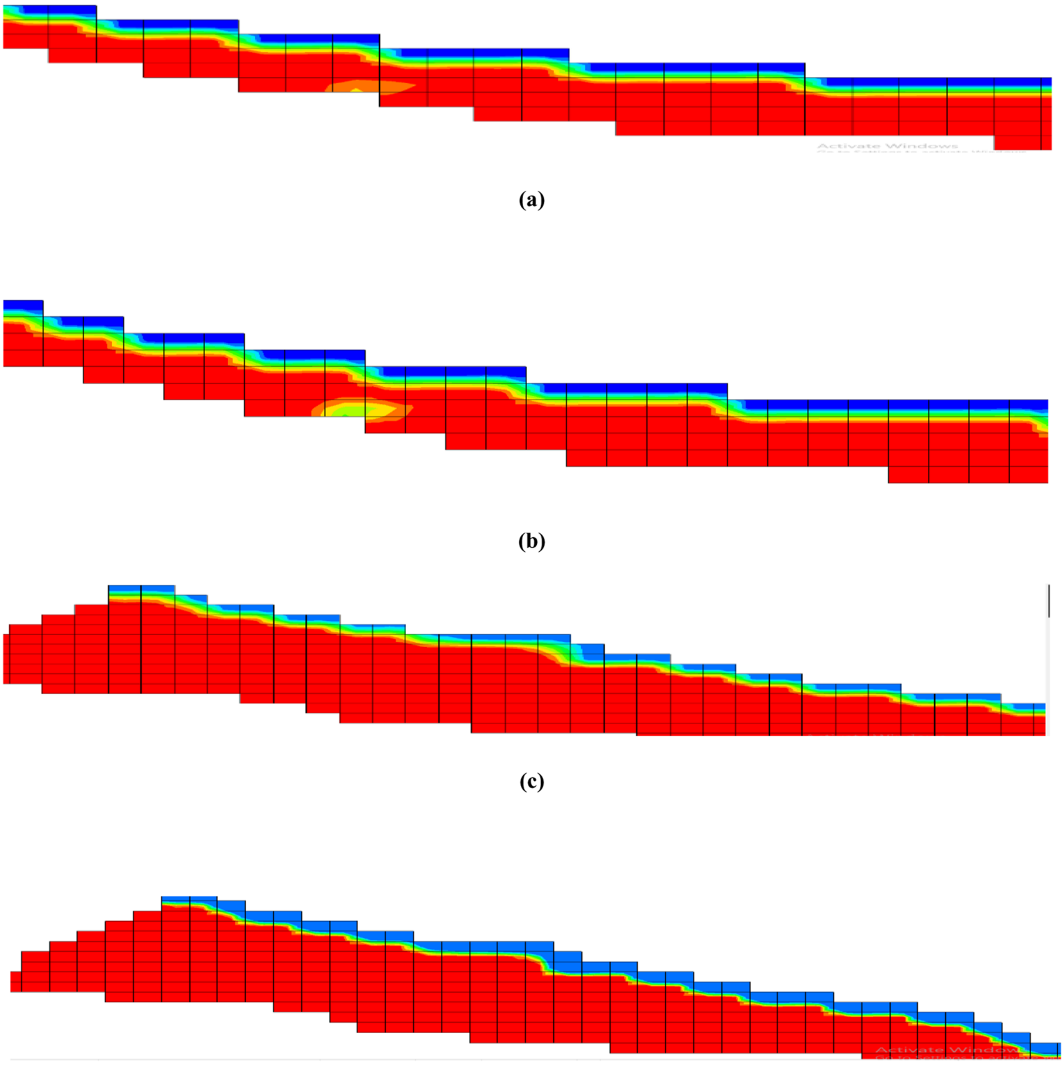


Fig. 8 Head of groundwater for each row after running scenarios in MODFLOW: **a** head of row 12 in each scenario, **b** head of row 26 in each scenario, and **c** head of row 41 in each scenario

cells containing fresh water, and other colors indicated regions of brackish water. For having an accurate investigation about effects of each scenario on lateral movement of sea water, the simulated rate of salt for column 11 is plotted in Fig. 10, so as to understand in which scenario sea water moves further and in which scenario rate of salinity is more than all of them. The most critical simulated situation for



(a)

(b)

(c)

(d)

Fig. 9 Lateral movement of sea water in SEAWAT: **a** lateral movement of salt water in scenario 5 on the starting day of the simulation, **b** lateral movement of salt water in scenario 5 on the last day of the simulation, **c** lateral movement of salt water in scenario 6 and scenario 5 on the starting day of the simulation, and **d** lateral movement of salt water in scenario 6 on the last day of the simulation

the lateral movement of sea water is for scenario number 5. Based on Fig. 10, interaction between fresh water and sea water happens in regions that the head of ground water is − 13 to − 15 m.

Calculating fresh water resources in future for each scenario

For evaluating the effects of each of the simulated scenario accurately, the total volume of freshwater with salinity less than 3 kg/m^3 was calculated at the end of each simulation. For this goal, number of cells located between 0 and 1500 m from the Caspian Sea containing freshwater was computed. Table 4 shows the simulation results based on Australian saline water boundary for delineating the freshwater–saltwater boundary. Also, the table summarizes predicted fresh water data which are the sums of data for the next 20 years. The values represented in the Table 4 shows that how much freshwater is sensitive to each scenario based on anthropogenic and climatic factors considered in

Table 4 Volume of calculate fresh water in each scenario

Scenario	Volume of fresh water (MCM)	Percentage	Changes in each scenario
1	5,140,000	100	0
3	4,120,000	80.11	19.89
4	448,000	87.13	12.87
5	4,000,000	77.77	22.23
6	4,330,000	84.21	15.79
7	4,270,000	83.04	16.96
8	4,300,000	83.62	16.38
9	4,330,000	84.21	15.79
10	3,010,000	81.87	18.13

the model. Scenario numbers 5 and 3 are less favorable scenarios. Based on all the calculated data in Table 4, fresh water in the fifth scenario will be decreased about 22% for the next 20 years, indicating that available volume of fresh water is more sensitive to pumping rate changes or anthropogenic changes yield by urbanization. Scenario number 4 which is about decrease in CSL has less effects on the volume of fresh water in the aquifer.

Conclusions

Nowshahr-Nur aquifer is located in north part of Iran. The north part of this region is connected to the Caspian Sea, the middle part includes plains and agricultural land, and the south part of this area is surrounded by Alborz mountain range. In recent years, water resources in this area are threatened by an increase in population, deforestation, and heavy and unpredictable floods which are caused by climate change and urbanization. In this research, the combined effects of future climate and anthropogenic changes on Nowshahr-Nur aquifer's groundwater system were studied. Ten scenarios that modeled LC/LU changes, climate changes, population changes, and CSL changes were used. The three-dimensional distribution of groundwater head and salt concentration levels was simulated using the SEAWAT and MODFLOW codes. The input recharge rate to SEAWAT was simulated using the SWAT code. Analytical results of future scenarios show that except the seventh and tenth scenarios, all of the scenarios resulted in a decrease in water level simulation in the next 20 years. Also, rate of decrease in scenario number 5 was more than that in other scenarios which showed that the case study is more sensitive to urbanization than to climate change. The simulation

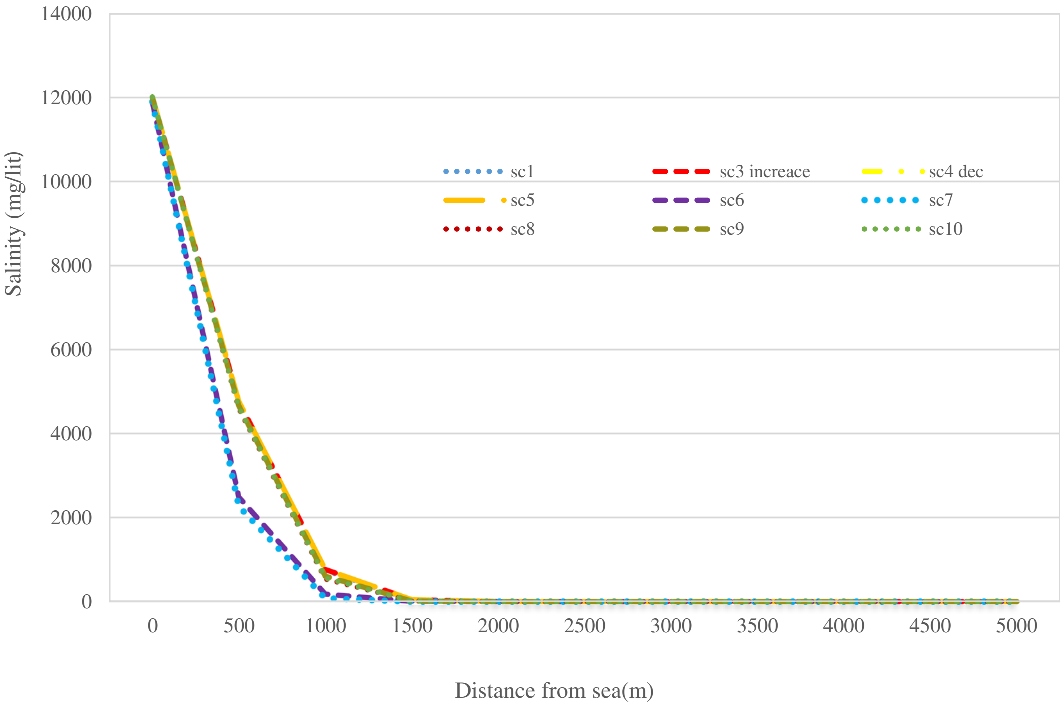


Fig. 10 Interaction between fresh water and sea water based on salinity in column 11

results indicated moderate SWI in all scenarios, the prominent reason of this phenomenon is for low level of the salinity in Caspian Sea. Salt concentration in the Caspian Sea is between 11 and 13 kg/m^3 so it does not cause concerning SWI. Lateral movement of sea water to coastal area does not exceed 1500 m and it is yield by the fifth scenario. Lateral movement of sea water in each scenario has direct effects on level of fresh water volume in the aquifer. Scenario numbers 5 and 6 decrease freshwater volume 3% in the next 20 years. This research provides an important source for studying the integrated effects of urbanization and climate change on groundwater resources by combining a watershed-scale model and a groundwater model. Another major contribution of this study is to use SWAT and SEAWAT codes simultaneously for simulating saltwater intrusion by designing some scenarios for a realistic field site. For managing groundwater sources in the future, we need reliable data which has analyzed all aspects of changes happening in the case study. There are just a limited number of studies analyzing a combination of all effects especially in urban areas; for example, Foster and Allen (2015) investigated effects of climate change and human's stressor on surface water and ground water interaction; Chang et al. (2016) analyzed effects of urbanization and climate change on ground water resources in a barrier inland but they did not explored effects of changes in sea level. Most of the studies explored one type of effects; for instance, Langevin and Panday (2012) showed how much of sea level rise impacts SWI near a coastal field; Park et al. (2011) evaluated various saltwater extraction schemes for diminishing SWI ascribed to groundwater pumping in a coastal aquifer system; Abbaspour et al. (2009) analyzed effects of climate change on water resources of Iran. Further studies are required to analyze these scenarios accurately. Moreover, for understanding uncertainties in all the parameters, more sensitivity studies are needed. The knowledge gained from such studies can be utilized to form better water management practices for coastal areas which are developing.

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