Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28722

269 (2022) 33–46
September

The vulnerability evaluation of groundwater level rising and development of irrigation network in Mian-Ab aquifer through Analytical Hierarchical Process method and groundwater modeling

Seyed Yahya Mirzaee Arjanki[a,*], Pooria Sheikhy[b], Manouchehr Chitsazan[c]

[a]*Earth Sciences Faculty, Shahid Chamran University of Ahvaz, Iran, Tel. +98613331059; Mobile: +989163096940; Fax: +98613331059; email: Yahyamirzaee@scu.ac.ir*
[b]*MSc of Hydrogeology, Abatipajooh Consulting Engineering Company, Ahvaz, Iran, email: Pooriasheikhy@yahoo.com*
[c]*Earth Sciences Faculty, Shahid Chamran University of Ahvaz, Iran, email: Chitsazan-m@scu.ac.ir*

Received 28 January 2022; Accepted 12 July 2022

ABSTRACT

Groundwater level rising in the plain of Mian-Ab located in Khuzestan Province, southwestern Iran, is one of the major threats to this region. Continuous recharge of the aquifer through returned water from irrigation canals as well as the spread of fine sediment particles along with other hydrological and hydrogeological factors have led to a decrease in groundwater quality and waterlogging of the areas under cultivation in the region. This study evaluated nine important hydrological and hydrogeological parameters using the Analytical Hierarchical Process method to detect the vulnerable zones in Mian-Ab aquifer regarding the groundwater level rising. The vulnerability map showed that some parts of northern, central and southern lands in the study area were in the medium and high waterlogging vulnerability. The groundwater flow in the aquifer was then simulated using the MODFLOW model to validate and verify the vulnerability map of the study area, and also to predict the aquifer behavior in case of developing an irrigation canal network in future. The model was calibrated from September 2016 to September 2017 in the unsteady state conditions with 0.94 RMSE error. The model was first executed with a 20 percent increase in the net recharge rate. Then, the vulnerability map was confirmed and validated in the MODFLOW model, given that the increase in groundwater level occurred precisely in the zones identified in the vulnerability map. In the next step, to evaluate the development of the irrigation network in the region, the future conditions were simulated therein. The model showed that the head would increase significantly about 2 to 4 m in the same zones where the vulnerability map detected, and the recharge rate increased about 13.28 MCM through the returned water of the future canals considering their dedicated specific flow rates. It is thus recommended that the network development program and net recharge allocation be adequately managed to prevent environmental problems in the southern parts of the study area.

Keywords: Groundwater level rising; Analytical Hierarchical Process; Geographical Information System; MODFLOW 2000; Groundwater Modeling System; Mian-Ab

1. Introduction

Groundwater is always considered as one of the most determinative factors for urban and agricultural development. Evaluating and predicting groundwater level is indeed an important part of groundwater resource management [1]. Rising in groundwater level can cause different environmental problems such as marshy lands, reduced groundwater quality, and extensive urban construction damages. On the other hand, in areas where agriculture

* Corresponding author.

is widespread, rising groundwater level can lead to water contamination by chemical fertilizers and soil texture damage as a result of the evaporation process and increased soil salinity. Therefore, monitoring rising groundwater level in aquifers seems indispensable.

As annual rainfall is usually low and uncertain in arid regions, groundwater and irrigation networks supply crop water requirements in these areas. As such, waterlogging has been recognized as a threat for the aquifer due to intensive seepage (as returned water) into the groundwater [2]. Waterlogging has been reported in some regions of Khuzestan Province including Mian-Ab plain and Behbahan Plain, southwest of Iran, due to reduction in aquifer exploitation and increase in groundwater recharge resulting from return irrigation water [3]. The agricultural lands cover more than 70% of Mian-Ab plain, and most of the crop water requirements are supplied through the irrigation canal network. As rising groundwater level is a threat to Mian-Ab plain, this study was intended to evaluate Mian-Ab aquifer in terms of waterlogging vulnerability through the Analytical Hierarchical Process (AHP) method and groundwater modeling.

The AHP method developed by Saaty (1980) [4] provides the best choice among different alternatives based on a series of criteria or variables. In the AHP processing, the limitation in the capacity of processing options is resolved by using paired comparison [5]. The AHP method can serve as a powerful tool for solving complicated problems involving several objectives [6]. It helps water resources managers explore and evaluate vulnerable zones of the aquifer in terms of contamination and waterlogging or find the best zones for the artificial recharge. The starting point for this purpose is to face different alternatives. Each alternative has some criteria that determine its characteristics and it is these characteristics that determine an alternative as the optimal choice. The next step is to define and weigh the relative importance of each criterion. The criteria are indeed compared in a pairwise manner based on a scale proposed by Saaty, as shown in Table 1. After generating a hierarchy, a pairwise-comparison matrix of each element is built using the comparisons. Then, the eigenvector of the matrix shows the weight or importance of each criterion. The final proposed map can be produced using the Geographical Information System (GIS) to determine the weight and importance of the thematic layers. The final vulnerability map produced in GIS can be then imported to the Groundwater Modeling System (GMS). This, in turn, help verify the vulnerability map for the management of the aquifer by using numerical models.

The numerical models have been already used to monitor, control, and manage groundwater resources in the early years of the 20th century. Using groundwater models can help figure out the head distribution, flow patterns, and also predict future hydrodynamic conditions of the aquifer [7]. A groundwater model is a tool for simulating the groundwater flow system more straightforwardly than the field conditions. Using the groundwater model, one can make a conceptual or graphical expression of the aquifer system using mathematical equations. Such models represent a complex system so that its behavior and the relationships between the variables and parameters of the model are expressed by mathematical expressions or sometimes by logical terms. Mathematical models are, in fact, solutions to the basic equations governing groundwater flow. The basis of the work of these models is the selection of differential equations governing the problem, replacing them with a system of equations by the finite difference method or finite elements, the characteristic method, and finally solving that system of equations by one of the relevant numerical methods by computer. A mathematical groundwater flow model consists of a governing equation which is combined with Darcy's law and water mass balance [8]. According to Darcy's law, the groundwater moves from areas with higher energy levels to areas with lower energy levels. The equations governing groundwater flow are generally derived from Darcy's law (1856) and its generalization to the three-dimensional state, the continuity equation (expanded by Slishter, 1889), Jacob's equation (1950), and Laplace's equation. The model synthesizes the field information and conceptualizes hydrogeological processes by providing a quantitative framework [9]. Groundwater model is a suitable management tool to identify the effects of future human activities and urban development on groundwater dynamics. The 3D flow equation which is used for most modeling codes calculates groundwater flow under unsteady-state, heterogeneous, and anisotropic conditions as follows [10]:

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right]-w=S_s\frac{\partial h}{\partial t} \quad (1)$$

Table 1
Fundamental scale of absolute numbers for paired comparison

Intensity of importance	Definitions	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one activity over another
5	Strong importance	Experience or judgment strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another
9	Extreme importance	Evidence favouring one activity over another is of the highest possible order of affirmation

where h, w, S_s and t are the hydraulic head, volumetric flux, specific storage coefficient, and time, respectively. K_{xx}, K_{yy}, and K_{zz} stand for the hydraulic conductivities along x, y, and z-directions, respectively.

There would be some requirements to manage groundwater effectively. First, the aquifer system should be adequately understood. Second, the water table measurements should be used to control the aquifer exploitation, and third, the aquifer should be recharged artificially in the case of overexploitation. It is thus necessary to study the aquifer response against different hydrological and hydrogeological stresses. Numerical models have been recognized as efficient management tools in groundwater studies. In the past few years, numerical models have been developed to study and manage the aquifers. In the early years of the 20th century (in the 1960s), mathematical models with numerical solutions became one of the most desirable methods in studying groundwater resources due to the development of advanced computers. Faust and Mercer first used mathematical models for groundwater modeling [11]. McDonald and Harbaugh [12] offered the MODFLOW computer. Wels and Findlater [13] successfully applied MODFLOW and an MT3D to predict the timing and magnitude of peak zinc concentrations in south Darwin. In a similar strand, Xu et al. [14] integrated the MODFLOW and SWAP model for modeling groundwater dynamics in shallow water table areas in Australia.

In Mian-Ab, more than 70% of the area is covered by agricultural lands, and most of the crop water demands are supplied by irrigation canal network. As a result, the aquifer in Mian-Ab is regularly recharged by intense seepage from agricultural lands. On the other hand, the irrigation canal network is under development in the southern parts of Mian-Ab plain to help irrigation purposes. To reconnoiter the vulnerable zones in the aquifer, its vulnerability in terms of groundwater level rising was thus evaluated by different hydrogeological thematic layers using ArcGIS10.3.1 software. The numerical modeling of the groundwater system in Mian-Ab plain was carried out, using GMS10.1 software and MODFLOW2000 code, to examine the behavior of the groundwater in the vulnerable zones. The proposed map was then imported to the GMS to observe the aquifer response in terms of groundwater level rising in the area. Considering the influential factors, the potential groundwater level rising could be then examined and managed.

2. Material and methods

2.1. Study area

Mian-Ab plain extends over about 640 km^2 in the northern part of Khuzestan Province, southwest of Iran (Fig. 1). The study area is mostly a flat plain with high and average altitudes of 101 m and 30 m above sea level. The land in the study area has a gentle slope (mainly

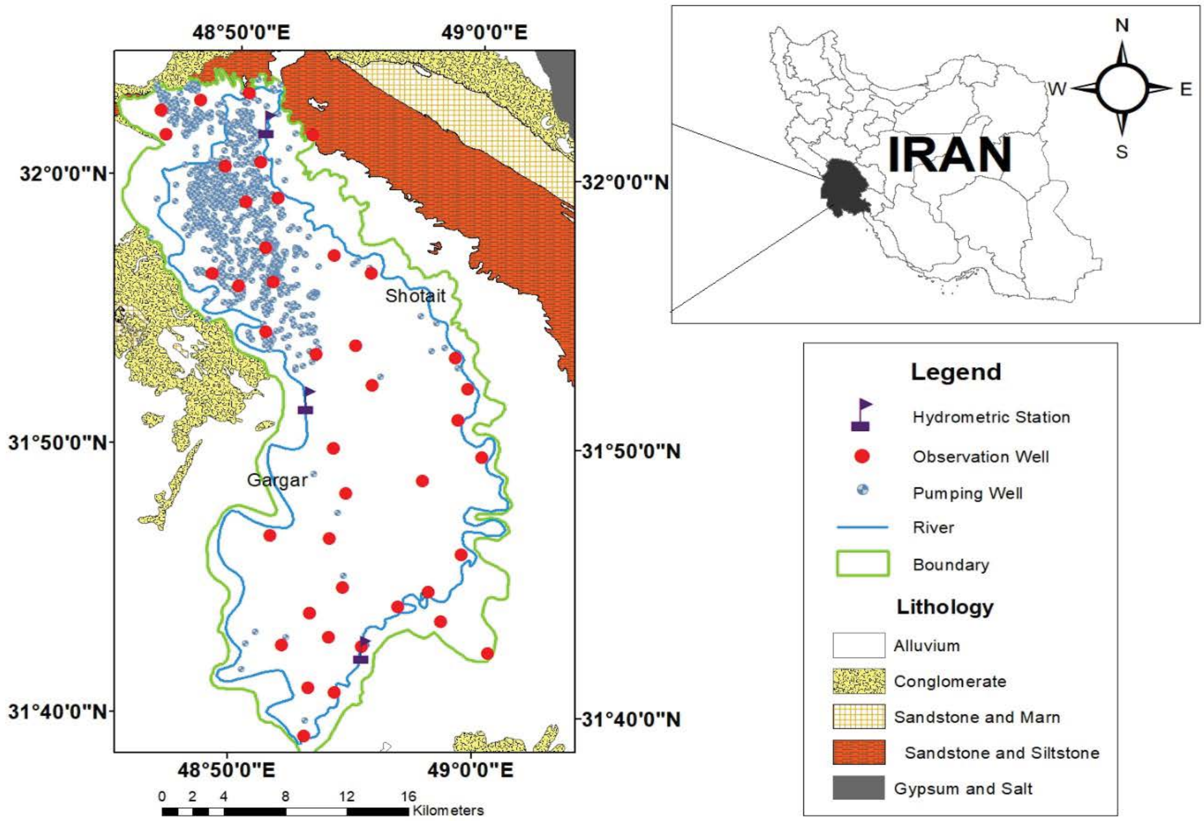

Fig. 1. Location and the geological sketch of Mian-Ab plain, SW Iran.

between 0.02%–0.7%), but it has some topographic features in some areas, and the main slope decreases from north to south. From a geological point of view, the Mian-Ab plain is part of the Zagros thrust and folded belt. The Zagros thrust and folded belt starts from the northwestern borders of Iran and continues to Bandar-Abbas region. The deformations along this belt started from the middle phases of the Alps (late Oligocene). Finally, in the Pasadenan phase (Plio-Pleistocene) the current appearance of the region has occurred. The geological units which have outcropped in the area belong to the late Pliocene, and alluvial and recent deposits mostly cover the central part of the plain. The recent alluvium deposits include fine-grained alluvial, flood, Aeolian, and evaporate sediments that appeared in the area. The Mian-Ab aquifer is limited from east and southeast by a sandstone/siltstone formation (Aghajari Formation) which significantly impacts the aquifer qualitatively and quantitatively. This formation in the adjacent areas mainly consists of brown (to gray) limestone and siltstone with layers of clay, marl, gypsum, and hard sandstones. Worn siltstone, the upper part of the Aghajari Formation, is called Lahbari member. Bakhtiary Formation, with the lithology of calcareous conglomerate, surrounds the study area in the north, northwest, and west. A general review of subsurface lithology shows that sediments in the north of the plain are coarser than those in other parts. The climate of Mian-Ab is arid with a mean annual temperature of 38.8°C and an average yearly rainfall of 250 mm. The highest precipitation in the study area is in winter, so 86% of the total rainfall occurs in winter, 10% in autumn, and about 4% in spring. The Ombrothermic curve also shows that the region had the most rainfall in December and January. The area also spends seven months of the year (May to November) in the dry season and another five months (December to April) in the wet season. The Karun River in the north of Shoushtar city (northeast of Khuzestan Province) is divided into two main branches, namely Gargar and Shotait, located in the east and west of the study area. These branches join each other in the south of Mian-Ab plain. Most of Karun's flow transfers to the Shotait when it divides into two branches north of Shoushtar city. The general slope of the Karun River and its ditches in Khuzestan is usually to the south. A network of canals conducts the water from the river branches to the farms in the region for irrigation purposes which, in turn, optimizes the use of surface water resources. The irrigation network in the Mian-Ab plain conducts the water from Gargar and Shotait rivers to the farming lands through the first and second-grade canals.

2.2. AHP method and thematic layers

The AHP method was used to assess the vulnerability of the aquifer in terms of groundwater level rising. Given that a variety of hydrological and hydrogeological factors are involved in groundwater level rising, the AHP method defines these factors as criteria. According to the hydrological and hydrogeological conditions in the study area, nine important factors evaluate groundwater levels rising in the aquifer. These factors, which are used as thematic layers, are aquifer recharge (precipitation and net recharge), soil media, groundwater depth, vadose zone thickness, hydraulic conductivity, aquifer media, exploitation (wells density), drainage density, and land use. In the first step, the thematic layers of each one of the factors were produced in ArcGIS10.3.1. Then, the rank of each thematic layer was determined in ArcGIS using reclassify extension in 9 classes (Fig. 2). The rank 1 means that the desired value is suitable, and the closer the values are to rank 9, the less appropriate they are. The ranks of thematic layers are shown in Table 2.

After producing and ranking the layers, to determine the importance and weight of each layer for detecting the vulnerable zones in the aquifer in terms of groundwater level rising, the researchers conducted pairwise comparisons between criteria using the AHP method (Table 3). The results of these comparisons were entered as a matrix into Expert Choice software and the weight of each criterion was then determined. Based on the findings, the hydraulic conductivity factor had the highest weight (0.191), while the soil media factor (0.033) showed the lowest weight. Thus, all nine layers were combined using weight overlay extension in ArcGIS, and the vulnerable zones of the aquifer were detected accordingly (Fig. 3). Three categories of low, medium, and high vulnerability were used to classify the vulnerability of the aquifer in terms of groundwater level rising. The final vulnerability map, if verified, can help manage groundwater resources and accurately predict the aquifer behavior in terms of groundwater level rising. To validate the vulnerability map, by constructing a mathematical model of groundwater in the study area, the researchers closely examined the final vulnerability map. The groundwater model can show the aquifer behavior considering its dynamic parameters such as hydraulic conductivity, and specific yield, etc.

2.3. Conceptual model and model design

After defining the purpose of groundwater modeling, namely simulating groundwater levels in vulnerable zones, the aquifer conceptual model was developed and valuable information about the boundaries, hydrostratigraphy, and hydrogeologic properties of the aquifer was provided. The combination of such information led to the development of a conceptual model for the region [15]. Mian-Ab aquifer is considered to be an unconfined aquifer composed of alluvium and recent deposits. The general direction of groundwater flow in the study area is from north to south based on the present data. The maximum thickness of aquifer in the north of the study area is 182 m, and the minimum thickness of the aquifer in the south of the aquifer is 109 m. The transmissivity (T) of the aquifer varies between 32 and 610 m^2/d, and the average specific yield (Sy) is about 0.09. All the hydrodynamic parameters decrease from north to south of the study area due to increasing silt, clay, and fine particles. The primary inflow sources of water to the aquifer are recharged by Gargar and Shotait rivers in the northern and central parts of the study area, and also through rain, and runoff infiltration of irrigation canals. The central aquifer outflows are exploitation wells, the drains, and also the discharges of Gargar and Shotait rivers in the southern parts of the plain.

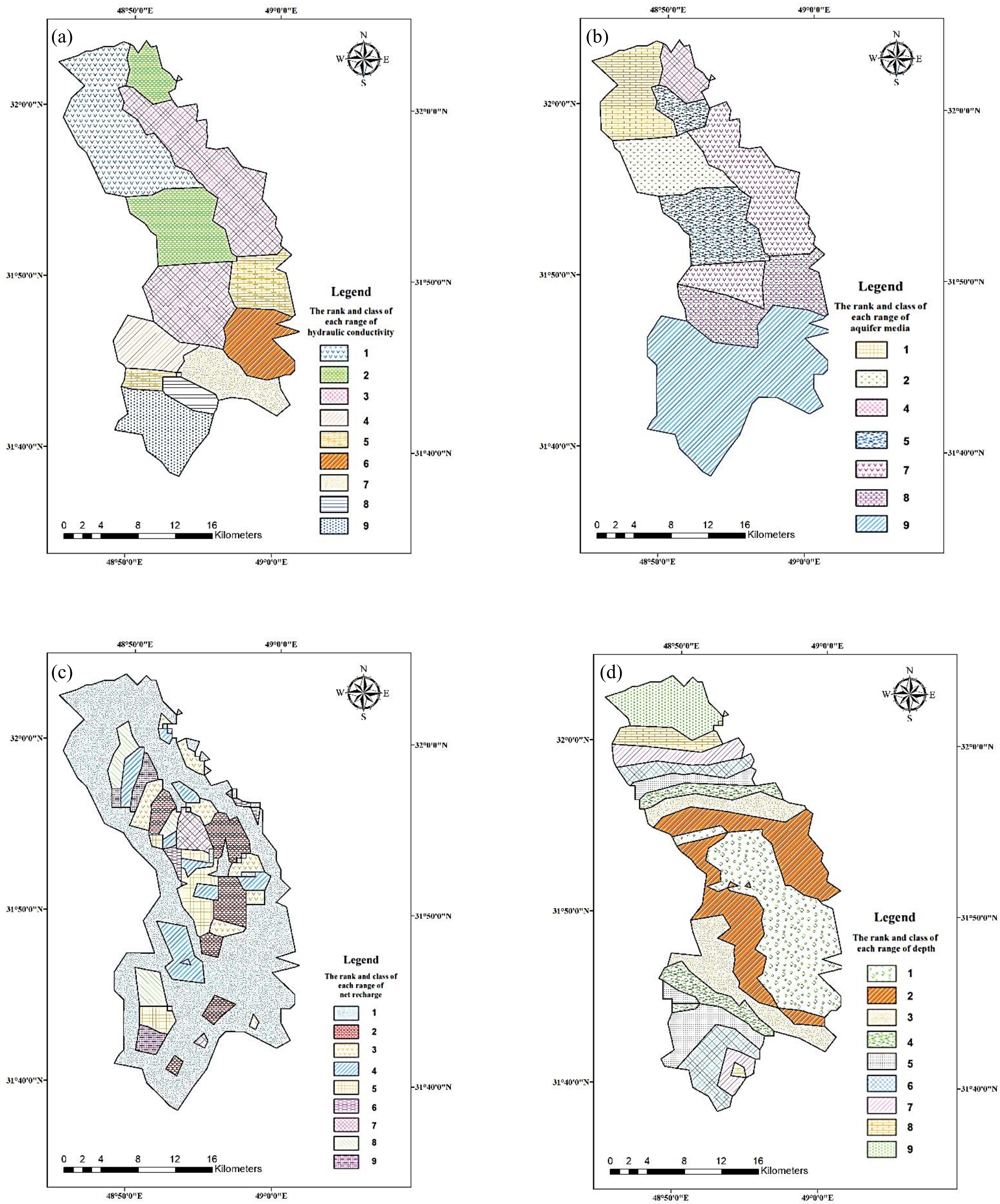

Fig. 2. (a) Hydraulic conductivity map, (b) aquifer media map, (c) net recharge map, and (d) depth map.

Table 2
Variation range and ranks of thematic layers

Criteria (thematic layer)	Variation range	Rank	Criteria (thematic layer)	Variation range	Rank
Aquifer recharge (cm/d)	0.61–1.75	1	Hydraulic conductivity (m/d)	0.2–0.56	9
	1.76–4.17	2		0.57–0.98	8
	4.18–6.88	3		0.99–1.45	7
	6.89–13.6	4		1.46–1.97	6
	13.61–23.65	5		1.98–2.49	5
	23.66–41.48	6		2.5–3.48	4
	41.49–68.61	7		3.49–6.98	3
	68.62–185.1	8		6.99–8.96	2
	185.11–286.79	9		8.97–13.5	1
Soil media	Silty loam	6	Exploitation wells density	0	9
	Clay loam	8		0.1–31.45	8
	Sandy loam	4		31.46–62.91	7
	Loamy sand	2		62.92–94.36	6
Groundwater depth (m)	3.25–3.94	9		94.37–251.65	5
	3.95–4.53	8		251.66–314.56	4
	4.54–5.3	7		314.57–377.47	3
	5.31–6.07	6		377.48–728.74	2
	6.08–6.77	5		728.75–1336.9	1
	6.78–7.48	4	Drainage density	0–0.11	9
	7.49–8.25	3		0.12–0.38	8
	8.26–9.05	2		0.39–0.64	7
	9.06–9.79	1		0.65–0.84	6
Vadose zone thickness (m)	1.7–3.27	9		0.85–1.01	5
	3.28–4.42	8		1.02–1.18	4
	4.43–5.56	7		1.19–1.45	3
	5.57–6.92	6		1.46–1.88	2
	6.93–8.42	5		1.89–2.53	1
	8.43–9.77	4	Aquifer media	Conglomerate	1
	9.78–11.06	3		Sand	2
	11.07–13.85	2		Clay	9
	13.86–19.92	1		Sand and silt	4
Land use	Barren land	1		Clay and silt	8
	Urban and rural areas	3		Silt and clay	7
	Agricultural lands	9		Silt	5

2.4. Model selection

Mian-Ab aquifer model was developed using Groundwater Modeling System (GMS) software and MODFFLOW code. The MODFLOW package discretizes the domain of the study area horizontally and vertically into the smaller components called the cell, and then the groundwater flow equation is solved for each cell. The MODFLOW provides the 3D simulation of flow paths and can simulate the aquifer and the interactions of adjacent hydrogeological units. These features helped quantify the groundwater resources of Mian-Ab plain, and also obtain the required information so as to manage the aquifer properly.

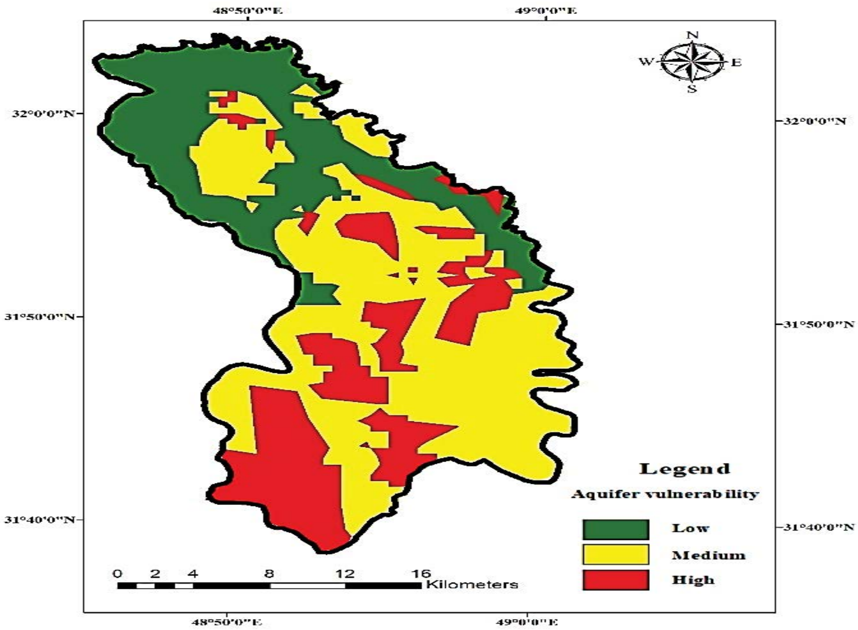

Fig. 3. Final map of groundwater level rising vulnerability.

2.5. Model discretization

As mentioned earlier, the numerical groundwater flow simulation of Mian-Ab aquifer was implemented using the MODFLOW2000 code with GMS software. The study area was represented horizontally on a three-dimensional grid and vertically as a single unconfined layer. The grid was discrete to 51 columns and 94 rows with 500 m × 500 m by a finite difference grid.

2.6. Database

To model a groundwater system, the researchers constructed a conceptual hydrogeological model representing the groundwater flow system using all available data. The conceptual model was generated using hydrological and hydrogeological data [16] such as hydraulic conductivity, water table levels in observation wells, recharge rate, discharge rate by wells and drainage ditches, boundary conditions, as well as top and bottom elevations of the aquifer. Data from 40 observation wells were imported into the model using the observation coverage ability in the GMS interface. The relevant packages defined other layers, including rivers, GHBs, irrigation canals, drainage ditches, pumping wells, rain recharge, and hydraulic parameters.

2.7. Boundary condition

To characterize the interaction between the rivers and the alluvial aquifer in the study area, the river water table and bed evaluation data of the Gargar and Shotait rivers were obtained from gauging sites and river cross-sections. According to the geological map, groundwater table map, and general direction of flow maps, the east-southeast boundary is surrounded by badlands of the Siltstone and Marn Formations in the area, in the form of the recent alluvium, which has acted as a physical and impenetrable boundary. The northern, northeastern, and northwestern aquifer boundaries were considered as groundwater inflow boundaries, and the southern and southern west aquifer boundaries were identified as groundwater outflow boundaries. Likewise, general head boundaries, as the head-dependent flux boundary, were assigned to all in/outflow boundaries in the model domain.

2.8. Sources and sinks

Initial values of the surface recharge including rain and returned flow of agricultural wells and irrigation canals were prepared based on the zoning maps of soil texture. Therefore, according to the soil texture, the rain penetration percentage was considered between 9% and 17%. The final value of the recharge was estimated during calibration due to the abundance of the agricultural returned flow and irrigation network seepage in the study area. Hydraulic conductivities estimated from geophysics surveys and well logs were used as initial values for the calibration. Pumping wells in the model were applied monthly according to the discharge rates. The discharge rates were, in turn, calculated based on the operating time per season. After converting the conceptual model into grid cells, the numerical model was run in steady and unsteady states. Then, the initial values of hydrological and hydrogeological parameters were calibrated according to the field conditions.

2.9. Model calibration

One of the most critical steps in groundwater modeling is the calibration of uncertain parameters, as their accurate estimation is not possible anywhere in the catchment area or

Table 3
Pairwise comparison and weight of layers

Criterion	Vadose zone thickness	Aquifer recharge	Exploitation wells density	Groundwater depth	Land use	Hydraulic conductivity	Soil media	Aquifer media	Drainage density	Layer weight
Vadose zone thickness	1	2	3	2	2	1	4	0.5	2	0.151
Aquifer recharge	0.5	1	4	3	1	0.33	4	0.33	3	0.122
Exploitation wells density	0.33	0.25	1	0.25	0.33	0.33	2	3	1	0.043
Groundwater depth	0.5	0.33	4	1	0.5	0.5	5	0.5	5	0.105
Land use	0.5	1	3	2	1	0.5	6	0.5	6	0.134
Hydraulic conductivity	1	3	3	2	2	1	3	2	3	0.191
Soil media	0.25	0.25	0.5	0.2	0.16	0.33	1	0.5	0.33	0.033
Aquifer media	2	3	0.33	2	2	0.5	2	1	3	0.175
Drainage density	0.5	0.33	1	0.2	0.16	0.33	3	0.33	1	0.047
Inconsistency	0.08									

Table 4
Different statistical errors of steady and unsteady model

Error (unit: m)	Model condition	
	Steady	Unsteady
Mean error (ME)	0.28 m	0.29 m
Mean absolute error (MAR)	0.52 m	0.78 m
Root mean squared error (RMSE)	0.62 m	0.94 m

aquifer. The GMS software provides a suitable instrument for calibrating various parameters. The allowed difference between the computed and observed heads is introduced as the interval to the GMS software. In this research, an interval of ±1 m was thus introduced to the model as an allowed discrepancy or error. At this stage, the parameters generally associated with uncertainty and their estimation are not possible everywhere in the catchment or aquifer and were calibrated. The calibration process was then performed using the manual method (i.e., trial and error method) and the automatic method (PEST) in steady and unsteady conditions.

3. Results and discussion

3.1. Steady-state conditions

The aim of the steady-state calibration was to estimate the distribution of hydraulic conductivities. For this purpose, both trial and error and PEST methods were used to reach the best match between the computed and observed heads during the consecutive model runs. The model was calibrated in a steady-state in 40 observation wells distributed in the study area in September 2016. Fig. 4 shows the best fit between the computed and observed heads and some statistical errors (especially RMSE) in the last steady-state model execution.

3.2. Unsteady-state conditions

The unsteady-state model requires temporal discretization in time steps and stress periods to properly show the changes in hydraulic heads. The time discretization in Mian-Ab MODFLOW model started from September 2016 to September 2017 in 365 d in 12 stress periods, and each stress period was a time step (30 d). In the transient conditions, related data such as recharge from rainfall and returned water of irrigation canals, river head stages, pumping rate, and boundary head proportional to the stress length of the periods entered the model and the head calculated in the steady-state model was used as the starting head. This condition also required the introduction of a new parameter called the specific yield of the aquifer. The specific yield of Mian-Ab aquifer varies between 23% and 2% based on pumping tests, geophysical studies, and well logs in the study area. The transient model calibration carried out based on calculated and observed heads best fitted in 40 observation wells. This stage was performed by trial and error adjustment of hydraulic parameters such as specific yield, river head stages, and recharge rates.

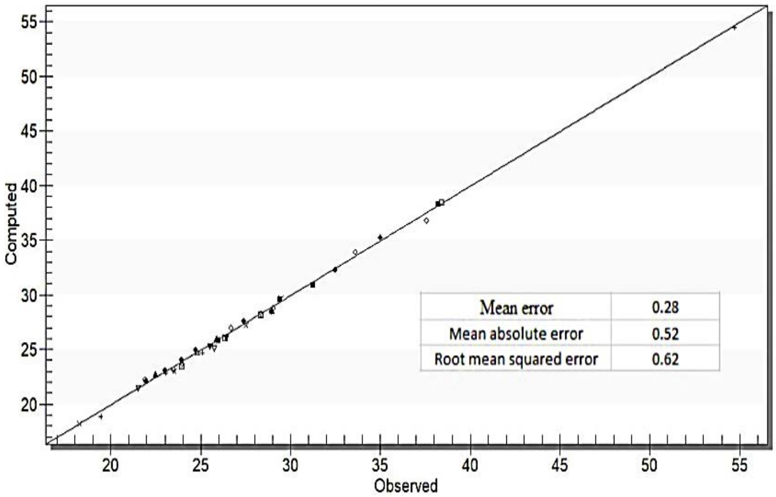

Fig. 4. Observed vs. computed heads and statistical errors in the steady-state model.

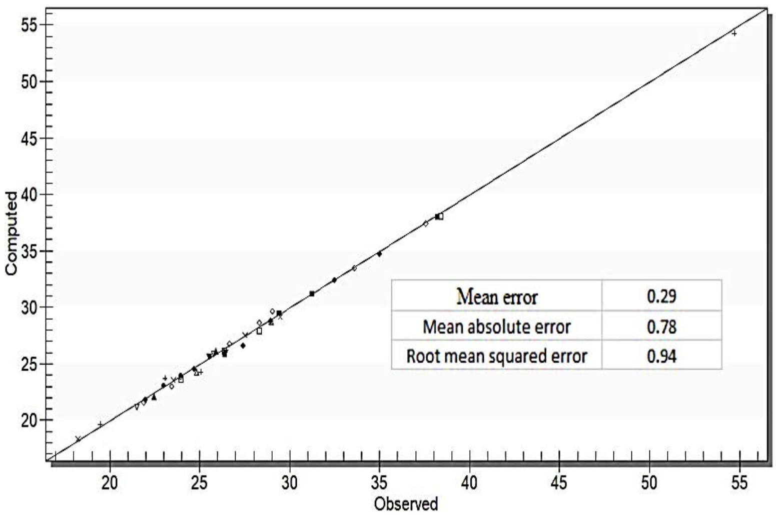

Fig. 5. Observed vs. computed heads and statistical errors in the unsteady-state model.

Fig. 5 shows the best fit between the computed and observed heads in the final stress period of the last execution and some statistical errors for the transient state calibration.

3.3. Sensitivity analysis

After calibration, the sensitivity analysis process was performed. Based on the definitions provided by Anderson et al. (2015), parameters were calibrated that were uncertain. The calibrated parameters in this research, in different stages of model execution, include hydraulic conductivity (K), specific yield (SY), general head boundaries (GHB), river conductance, GHB's conductance of model boundaries, and network recharge. Manual sensitivity analysis is one of the methods for sensitivity analysis (Table 4). In this method, the sensitivity of a given parameter will be determined by fixing all calibration parameters at their calibrated values except for the selected parameter, which was varied in sequential forward runs of the model by incrementally increasing and decreasing its value by some percent from its calibrated value.

In this research, the parameters were selected as the objective function for sensitivity analysis that has the most uncertainty in the region (hydraulic conductivity, specific yield, and GHB cells), as well as parameters that played an essential role in recharging and draining the aquifer (network recharge and exploitation wells) (Fig. 6). Then, to determine the most influential factors and the model's sensitivity to the considered parameters, each parameter separately had a 50% increase in values, and the model was executed. Finally, the model's sensitivity to the mentioned parameters was investigated by comparing the change values of different model errors. Based on the results and the difference in the absolute magnitude of the RMSE error related to each parameter before and after the sensitivity analysis operation, it was determined

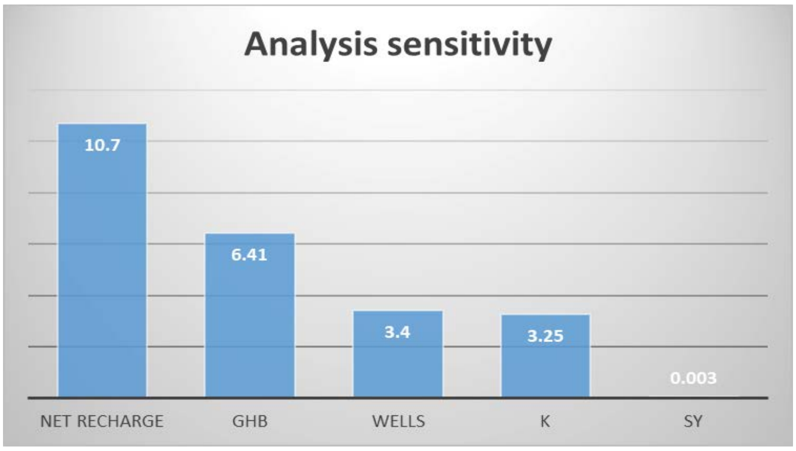

Fig. 6. Sensitivity analysis of the calibrated model.

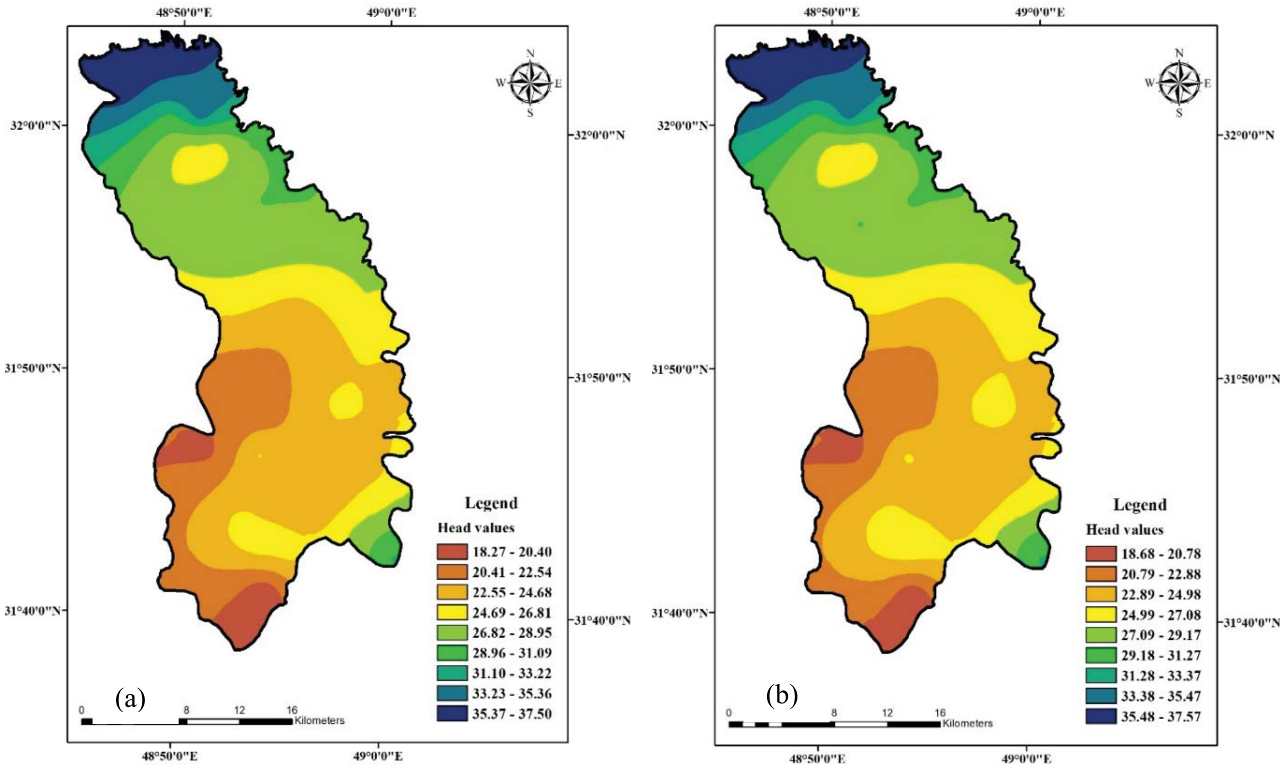

Fig. 7. Comparison between the simulated groundwater level before (a) and after (b) increasing the net recharge rate in the prediction model.

that the model has the highest sensitivity to the parameters of net recharge, GHB, exploiting wells flow rate, hydraulic conductivity and specific yield, respectively (Fig. 6).

3.4. Model verification

The model verification was performed from September 2017 to February 2018 in six stress periods. Reasonable agreement was obtained between the observed and computed heads in observation wells, given that the RMSE error of the validation model was calculated to be 0.95. After the validation period, the model balance was calculated using the Budget package. Based on the results, the groundwater balance in the modeled period (from September 2016 to September 2017) shows a change of about minus 2 MCM in the reservoir (Table 5).

The difference in total input and output of water in an aquifer system is called the water budget. The different components of the groundwater balance provide information about the states of inputs and outputs of water in an aquifer system. The calculation of water budget is one of the components of the conceptual model [17]. To that end, the water budget was calculated manually based on the field data; then the results were compared with the computed water budget through the calibrated model. The difference between calculated (based on the field data) and computed (based on the calibrated model) balance revealed that water balance calculations were fairly dependable (Table 5).

3.5. Evaluation of the vulnerability map using the prediction model

Models simulate the field situation by considering its hydrological and hydrogeological conditions and can thus predict future hydrodynamic conditions of the aquifer under different situations. The simulated model can serve to validate and verify the vulnerability map produced in ArcGIS. To this end, the prediction model was executed from September 2017, as the initial conditions, to September 2018. Then, the vulnerability map was imported to the GMS model as a new coverage. The net recharge rate was increased about 20 percent to evaluate both the vulnerability map and also the aquifer condition in terms of increasing irrigation canal flow rates resulting from network development. The prediction model was then executed with new recharge and flow rates. The head status of the aquifer is shown in Fig. 7 before and after applying new recharge rates. The residual contours of the water table show that the groundwater level rising occurred in the same zones detected on the vulnerability map for the groundwater level rising (Fig. 8).

3.6. Effect of future irrigation canals on Mian-Ab aquifer

There is already an irrigation and a drainage network in the study area intended to optimize surface water resources and help the agricultural boom. The irrigation network in Mian-Ab plain conducts water from Gargar and Shotait rivers to the farming lands through the first and second-grade canals. Based on the type and texture of the soil, the type of vegetation and the amount of specific flow

Table 5
Summary of calculated water budget parameters using field data and calibrated model

Water budget parameters	Flow in (MCM/y)*	Flow out (MCM/y)*	Flow in (m^3/y)	Flow out (m^3/y)
Wells	0	–94.24	0	–94,245,160
River	82.88	–47.32	83,106,032	–48,663,656
General heads	37.29	–20.94	37,723,776	–21,129,811
Drainage ditches	0	–49.86	0	–50,006,416
Net recharge	90.02	0	90,821,824	0
Total sources/sinks	210.19	–212.36	211,651,632	–214,045,043

*These values are calculated from filed data.

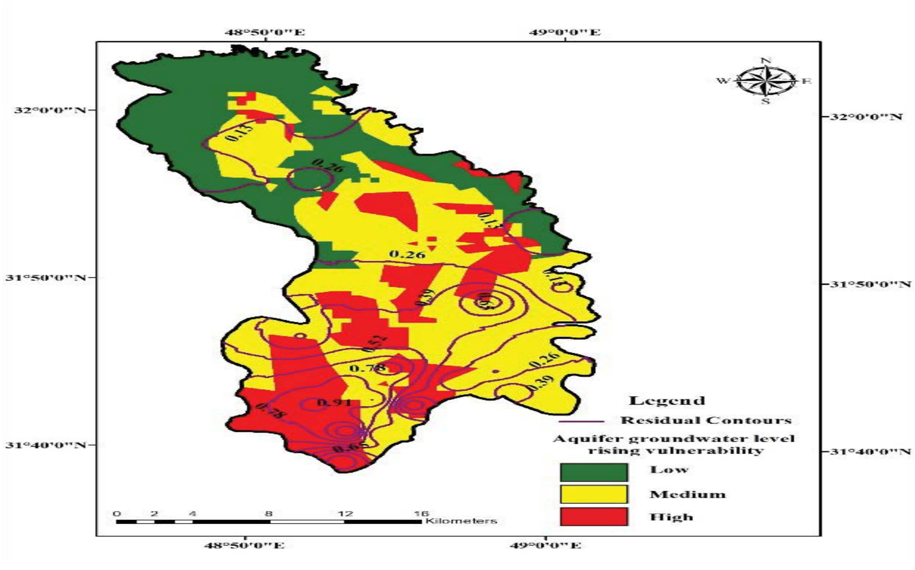

Fig. 8. Residual contours of simulated groundwater level before and after increasing net recharge rate.

Table 6
Summary of groundwater budget parameters after applying future canals in the model

Water budget parameters	Flow in (m^3/y)	Flow out (m^3/y)
Wells	0	–95,044,496
River	76,930,776	–51,059,232
General heads	21,176,542	–6,724,862
Drains	0	–50,001,132
Net recharge	104,191,968	0
Total sources/sinks	202,299,286	–202,829,722

rate to the canals, the spreading water on the ground infiltrates into the saturation zone of the aquifer and recharges it. The irrigation and drainage network now covers the northern and middle parts of the study area, and develops in the southern parts of the plain (Fig. 9). Due to the extension of marl and fine clay and the high groundwater level in the southern parts of Mian-Ab plain, the groundwater quality is not suitable for exploitation through the wells. As such, the development of an irrigation and drainage network in the southern regions can serve agricultural purposes. Khuzestan Water and Power Authority (KWPA) Company specifies the specific flow rates for future canals according to the water requirements of agricultural lands. It is estimated that 90 MCM of water is needed to meet agricultural water needs, considering the area of southern lands and cultivation patterns. Accordingly, the aquifer recharge will increase by the infiltration of excess water from new irrigation canals. After rerunning the MODFLOW prediction model (from September 2017 to September 2018) with new irrigation canals, the water budget calculations showed that the recharge rate increased about 13.28 MCM through the returned water of the new canals considering their dedicated specific flow rates (Table 6). The MODFLOW model shows that there will be a significant water level rising in the southern parts of the aquifer, which can lead to marshy lands and land leakage as a result of waterlogging in the study area (Fig. 10).

4. Conclusion

This study evaluated Mian-Ab aquifer in terms of groundwater level rising. As mentioned earlier, the aquifer is consistently recharged by the infiltration of excess water from the irrigation canal network used for agriculture. As such, the groundwater level rising can be considered a threat to the aquifer, but the aquifer has not experienced a groundwater level rising yet. The AHP method can be effectively used to recognize vulnerable zones in the aquifer in terms of groundwater level rising. According to the produced vulnerability map, the northern parts in the plain are mostly in the low vulnerable zones. However, the central and southern parts of the study area are in zones with

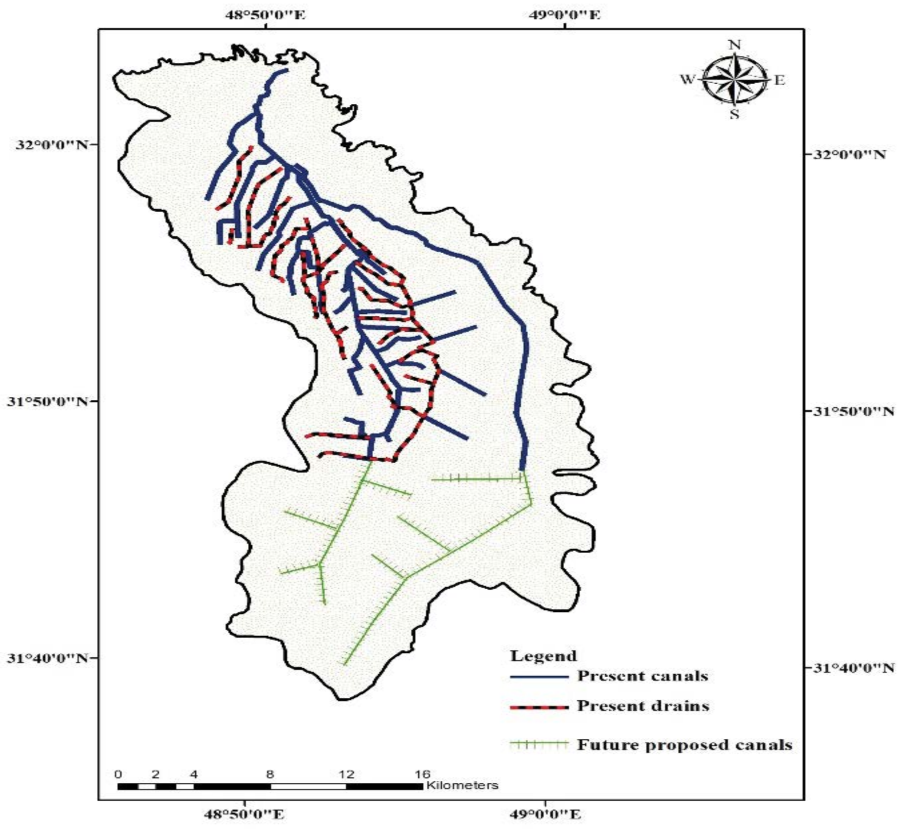

Fig. 9. Present and future proposed canals and drains.

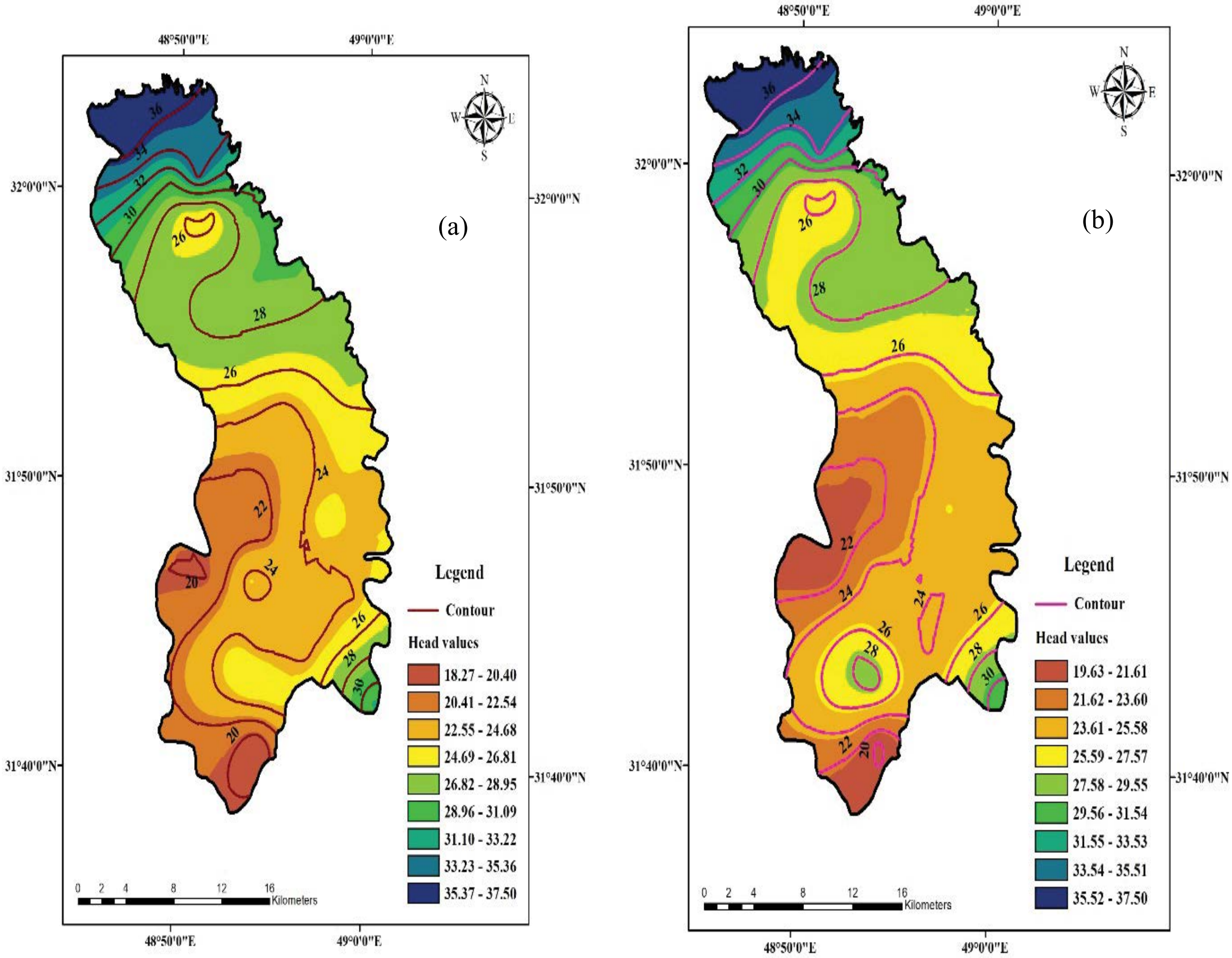

Fig. 10. Comparison between observed (a) and simulated groundwater level (b) due to network expansion.

medium and high vulnerability given that the particle size of sediments decreases from the north to the south, and the hydraulic conductivity values decrease consequently due to increasing silt clay and fine particles. In some parts of the northern lands, there is an uplift in bedrock which decreases the thickness of the vadose zone. Moreover, due to the excess seepage of water used for agriculture in the aquifer, it is fully recharged. Some parts of the northern lands, shown on the vulnerability map, are in the medium and high class of groundwater level rising. In the next step, the groundwater flow system in Mian-Ab aquifer was simulated using the MODFLOW code in the GMS interface so as to evaluate the aquifer behavior against the groundwater level rising. Based on the findings from the model, the net recharge rate increased 20%.

The MODFLOW prediction model and the vulnerability map yielded the same results. The head in the MODFLOW model increased significantly in the same zones identified by the vulnerability map. According to the gathered information on developing an irrigation canal network, to supply enough water for agricultural purposes in the southern lands of the study area, 90 MCM of water is needed. The MODFLOW prediction model was also executed with new irrigation canals in the southern parts and new flow rates so as to simulate the aquifer condition. The model showed that the head would increase significantly between 2 to 4 m. The water budget calculation also showed that the recharge rate increased about 13.28 MCM through the returned water from the new canals considering the dedicated specific flow rates of future channels. In case of developing an irrigation canal network in the southern parts of the study area, the model showed that there would be a groundwater level rising in the same zones where the vulnerability map already warned. It is thus recommended that the network development program and net recharge allocation be adequately managed so as to prevent environmental problems in the southern parts of the study area. Therefore, the network development plan and the amount of canals allocation discharge are suggested to be thoughtfully managed to prevent environmental problems in the south of the studied area.

Conflict of interests

Authors have no conflict of interests.

Acknowledgments

The authors are grateful to the Earth Sciences Faculty, Shahid Chamran University of Ahvaz, Iran for providing us for do this study.

Disclosure statement

No potential conflict of interest was reported by the authors.

Ethical approval

This study was originally approved by the Shahid Chamran University of Ahvaz, Ahvaz, Iran.

Authors contributions

Study concept, design and critical revision of the manuscript for important intellectual content: Seyed Yahya Mirzaee Aranki, Pooria Sheikhy, Manouchehr Chitsazan drafting of the manuscript and advisor: Seyed Yahya Mirzaee Aranki; performing the experiments Seyed Yahya Mirzaee Aranki, Pooria Sheikhy.

Funding

The work was financially supported by a grant (SCU.EG98.77) of Shahid Chamran University of Ahvaz, Iran.

Competing interests

Persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. The name of each author must appear at least once in each of the three categories below.

Category 1

Conception and design of study: Seyed Yahya Mirzaee Aranki, Pooria Sheikhy, Manouchehr Chitsazan

- acquisition of data: Seyed Yahya Mirzaee Aranki
- analysis and/or interpretation of data: Pooria Sheikhy, Manouchehr Chitsazan

Category 2

- Drafting the manuscript: Seyed Yahya Mirzaee Aranki, Pooria Sheikhy, Manouchehr Chitsazan
- revising the manuscript critically for important intellectual content: Seyed Yahya Mirzaee Aranki, Pooria Sheikhy

Category 3

Approval of the version of the manuscript to be published (the names of all authors must be listed): Seyed Yahya Mirzaee Aranki, Pooria Sheikhy, Manouchehr Chitsazan

References

[1] Y. Yihdego, C. Danis, A. Paffard, Why is the groundwater level rising? A case study using HARTT to simulate groundwater level dynamic, Water Environ. Res., 89 (2017) 2142–2152.
[2] A. Singh, P. Krause, S.N. Panda, W.-A. Flugel, Rising water table: a threat to sustainable agriculture in an irrigated semi-arid region of Haryana, India, Agric. Water Manage., 97 (2010) 1443–1451.
[3] H. Daneshian, N. Kalantari, Evaluation the performance of irrigation networks in groundwater level rising (case study Behbahan plain), Ecohydrology, 5 (2018) 135–148.
[4] D. Thirumalaivasan, M. Karmegam, K. Venugopal, AHP-DRASTIC: software for specific aquifer vulnerability assessment using DRASTIC model and GIS, Environ. Modell. Software, 18 (2003) 645–656.
[5] E. Cabrera Jr., R. Cobacho, V. Estruch-Guitart Vicent, J. Aznar, Analytical hierarchical process (AHP) as a decision support tool in water resources management, J. Water Supply Res. Technol. AQUA, 60 (2011) 343–351.
[6] P.-T. Chuang, Combining the analytic hierarchy process and quality function deployment for a location decision from a requirement perspective, Int. J. Adv. Manuf. Technol., 18 (2001) 842–849.
[7] H. Mohammadzadeh, M.A. Dadgar, H. Nassery, Prediction of the effect of water supplying from Shirindare dam on the Bojnourd aquifer using $MODFLOW_{2000}$, Water Resour., 44 (2017) 216–225.
[8] R.W.H. Carroll, G.M. Pohll, S. Earman, R.L. Hershey, A comparison of groundwater fluxes computed with MODFLOW and a mixing model using deuterium: application to the eastern Nevada Test Site and vicinity, J. Hydrol., 361 (2008) 371–385.
[9] M.P. Anderson, W.W. Woessner, R.J. Hunt, Applied Groundwater Modeling: Simulation of Flow and Advective Transport, Academic Press, London, 2015.
[10] J. Bear, Hydraulics of Groundwater, Dover Publications Inc, Mineola, New York, 2012.
[11] C.R. Faust, J.W. Mercer, Ground-water modeling: numerical models, Groundwater, 18 (1980) 395–409.
[12] M.G. McDonald, A.W. Harbaugh, A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, US Geological Survey, 1988.
[13] C. Wels, L.L. Findlater, Groundwater Modeling as a Tool for Closure Planning: Prediction of Zinc Transport for Alternative Cover Scenarios, 8th International Conference on Acid Rock Drainage (ICARD) and Securing the Future: Mining, Metals and the Environment in a Sustainable Society, Curran Associates Inc., Sweden, 2009, pp. 1217–1226.
[14] X. Xu, G. Huang, H. Zhan, Z. Qu, Q. Huang, Integration of SWAP and MODFLOW-2000 for modeling groundwater dynamics in shallow water table areas, J. Hydrol., 412 (2012) 170–181.
[15] N. Kresic, A. Mikszewski, Hydrogeological Conceptual Site Models: Data Analysis and Visualization, CRC Press, Taylor & Francis Group, Boca Raton, FL, 2012.
[16] A. Movahedian, M. Chitsazan, L. Nozarpour, Management of an aquifer with an emphasis on the interaction of the aquifer and river using MODFLOW model in Gotvand–Aghili plain, Khuzestan, Iran, Arabian J. Geosci., 9 (2016) 119, doi: org/10.1007/s12517-015-2121-z.
[17] S. Viaroli, L. Mastrorillo, F. Lotti, V. Paolucci, R. Mazza, The groundwater budget: a tool for preliminary estimation of the hydraulic connection between neighboring aquifers, J. Hydrol., 556 (2018) 72–86.