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Evaluation and Simulation of Groundwater Flow in Aquifers Enclosed With Desert Saline Areas (Case Study: Isfahan Province-Ardestan Aquifer)

Saman Javadi[a], Hamid Kardan Moghaddam[b,] and Aminreza Neshat[c]

[a] Department of Irrigation and Drainage Engineering, Aburaihan campus, University of Tehran, Tehran, Iran.
[b] Department of Water resources research, Water research institute, Ministry of Energy, Tehran, Iran.
[c] Department of GIS/RS, Faculty of Natural resources and Environment, Science and Research Branch, Islamic Azad University, Iran.

[*] Corresponding Author, E-mail address:
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Abstract
Quantitative changes in groundwater and crises resulting from uncontrolled water extraction have turned water resources management into one of the supply-demand dilemmas in arid regions. The present study evaluated the quantitative situation of water resources in the Ardestan Plain adjoining the Ardestan desert by using the MODFLOW mathematical model. Simulation of groundwater flow in the steady and non-steady states was carried out for a six-year period. Considering the trend of uncontrolled water extraction, results of the simulation also showed that there was a groundwater-level decline in the middle parts of the aquifer and smaller in its western parts. Analysis of the groundwater flow and the water resources balance in watershed basin indicated that in the outlet section of the aquifer the groundwater flow direction was reversed. Given the groundwater-level decline in the aquifer, the groundwater level was higher in the desert section and caused groundwater transfer from the desert to the aquifer. This suggests that the Ardestan aquifer will have environmental problems in its outlet section in addition to problems resulting from lack of water resources management and from the decline in groundwater level. This transport can increase with the continuation of the exploitation trend and also influence a larger part of the aquifer. Consequently, the results of the present research revealed that considering the recent droughts, groundwater extraction must be managed in order to improve the quality and quantity of water in desert aquifers.

Keywords: Aquifer, Modeling, Hydraulic gradient, Groundwater flow direction, MODFLOW.

1. Introduction

An indispensable source of water for human and environmental uses of groundwater is because of its overall quality and widespread occurrence (Cao et al., 2013). Various human-made and climate crises have complicated water resources systems. These crises have created various stresses from different viewpoints. Water resources evaluation can be accepted as one of the most important steps in increasing awareness and knowledge of the water resources situation. Results of water resources evaluation are effective and valuable for correct planning and management of water resources (Todd, 2005). Considering the population growth and the need for development in the different sectors, water use has increased considerably in these sectors. Under these conditions, unplanned water use in the agriculture sector, especially in arid regions where groundwater is the main water resource, has resulted in the severe groundwater-level decline and critical situations in Iranian aquifers. During the past two decades, the 75 billion m^3 reduction in the static groundwater reserves of the aquifers in the country has led to drying up of many groundwater resources, rivers, wetlands, orchards, and agricultural lands, qualitative decline in groundwater resources, land subsidence, disuse of more than 250,000 kilometers of water and wastewater networks, migration, squatter settlements, endangered political security, increased energy consumption, etc (Ministry of Power, 2014).

As the major water provision sources in arid regions, groundwater resources have faced many challenges in recent years. Climate change has taken place following increased greenhouse gas emissions on the one hand and lack of correct management for exploiting water resources, on the other hand, have severely reduced groundwater level in aquifers and the quality of this water. Nowadays, advances in technology and the use of computer tools in various sciences have resulted in using modeling techniques for simulating the existing situation. Use of mathematical models started in 800 AD. Following the expansion of advanced computers in the 1960s, employment of mathematical models that offer numerical solutions has turned into a desirable method in studying groundwater. Numerical methods in the form of differential equations were first developed by Mercer and Faust in 1980. In 1988, Wang and Anderson published the book Introduction to Groundwater Modeling: Finite Difference and Finite Element Methods (Harbaugh et al., 2000). This book introduced the use of the FORTRAN programming language to solve flow equations in porous media. Models are suitable tools for simulating groundwater flows. Extensive studies have been conducted on the use of mathematical models to identify the qualitative and quantitative situations in groundwater resources. Kardan Moghaddam et al (2018) who studied in birjand aquifer, Sheikhipour et al (2018) in shahrkord aquifer, Kardan Moghaddam and Banihabib (2017) sarayan aquifer, Jafari et al (2016) in saveh aquifer, Hamraz et al in birjand aquifer (2015), Rahnama and Zamzam (2013) the Rafsanjan aquifer, are among researchers who carried out simulation of the groundwater situation in Iran. Ehtiat et al (2018) Dehloran simulated integrated management using models swat and Moldflow. The results show the importance of integrated modeling tools for measuring the impact of changes in land and water resources in its underground water system.

Study of results obtained from simulating groundwater flow can serve as a suitable management tool because it shows the challenges that managers face and the potentials they can utilize in making decisions (Kardan Moghaddam et al., 2018). Although data uncertainty is inherent in models and modeling, use of models having suitable capabilities and developing strategies and scenarios can open specific horizons for developing groundwater resources and for achieving equilibrium in them. The present research intended to evaluate the quantitative situation of the Ardestan aquifer located in an arid region. This aquifer has been affected by various climatic stresses and over-discharge, and in recent years has increased the concentration of solutes, especially in aquifer outlet areas, due to the return of water from the desert side. Today, the most important discussion in the desert aquifer is the influx of saline fronts from the desert to the aquifer, which is important given the importance of groundwater resources in operation, and few studies have been done on this.

2. Research Tools

The numerical model MODFLOW in the GMS v10 software was employed to evaluate the quantitative situation in and the potentials of the Ardestan aquifer. Sensitivity analysis, calibration, and verification were performed to evaluate the model. Considering the boundary between the outflow of groundwater masses and the desert aquifer, the quantitative situation in this region was analyzed and evaluated. Figure (1) presents the research flowchart.

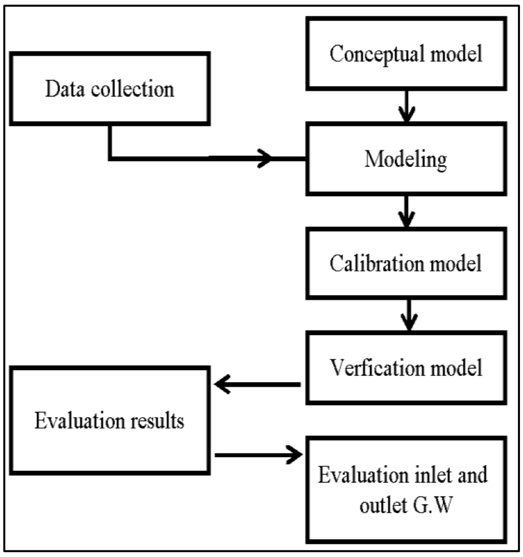


Fig 1. Flowchart of study

3. Case study

The study area in Ardestan (4,374 km^2: 2,160 km^2 in the plains region and 2,214 km^2 in the highlands overlooking them) is located in the Siahkooh Kavir Catchment Area in central Iran. The aquifer in the region is alluvial and has an area of 1,179 km^2. Based on the latest national inventory of water resources, there are 575 wells, 193 qanats, and 356 springs with the annual discharges of 156.3, 20.3 and 16.02 million m^3, respectively. The total annual volume of water used from the water resources in the study region in Ardestan is more than 180 million m^3 most of which is provided by groundwater resources and a small part by the transition flow to the Catchment Area. The annual volume of water used is more than 151 million m^3 in the plains region and more than 27 million m^3 in the highlands of the study area. The total volume of water used annually in the agriculture sector is more than 148 million m^3 in the plains region with the rest consumed in the highlands. Figure (2) shows the location of the study area, the plains region, and the Ardestan aquifer in Iran.

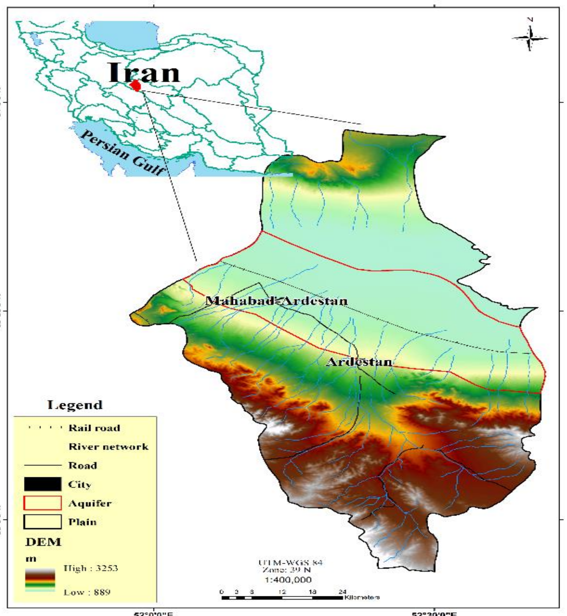


Fig 2. Case study

Numerical models of groundwater flow are based on solving two differential models with partial derivations: a 3D groundwater flows equation and a solute transport equation. The 3D groundwater flow equation with constant density in a porous medium is expressed as follows:

$$K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} + K_z \frac{\partial^2 h}{\partial z^2} - W = S_s \frac{\partial h}{\partial t} \quad (1)$$

Here, K represents hydraulic conductivity, h potential head, W volumetric flux per unit volume (to indicate discharge and recharge), S_s specific storage of the porous materials, t time, and x, y, z the Cartesian coordinates.

Determination of modeling dimensions and creation of a conceptual model are the first step in modeling to develop a mathematical model for simulating groundwater flow in a study region. In general, the goals in developing a mathematical model for groundwater flow can be expressed as follows:

- Explanation of the hydraulic coefficients of the aquifer.
- Spatial and temporal study of the water level in the aquifer and components of groundwater balance.
- Prediction of the quantitative situation in the aquifer.

Modeling groundwater is based on preparing a conceptual model that must be studied before beginning to model the aquifer situation with respect to the geometry, sources of discharge and recharge, and hydrodynamic coefficients of the aquifer. In fact, the conceptual presents a thorough interpretation of the actual conditions in the modeling range. Figure (3) presents a general schema of the conceptual aquifer.

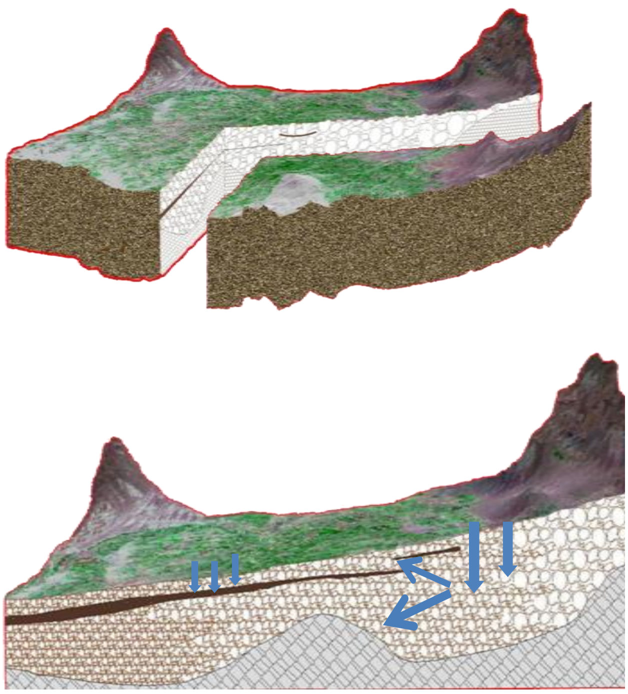
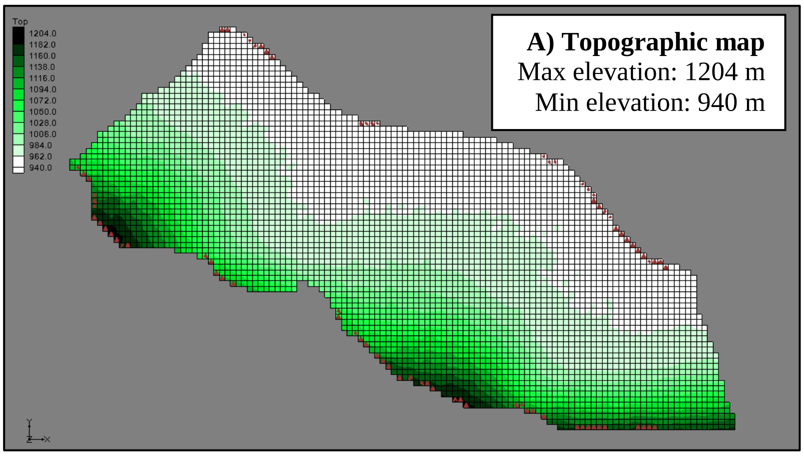


Fig 3. Conceptual model in Ardestan aquifer

The recharge and discharge sources of the aquifer, the boundary of the modeling range, water masses entering and leaving the aquifer, and also the structure of the aquifer must be described in the conceptual model. In fact, all factors influencing the aquifer must be considered. Since this aquifer is the only water resource for drinking water and water needed in the agriculture and industry sectors, excessive water extraction from it has caused a severe decline in the regional water table. In addition to the drop in the water table, the critical quantitative situation in this Plain has been accompanied by extensive negative changes in the quality of the aquifer. Therefore, a 6-year period was considered for modeling in order to study the quantitative situation of the aquifer. After developing a conceptual model to simulate groundwater flow, the Finite Difference Method was employed to solve the model. A problem-solving network in the form of a square cell with dimensions of 500*500 meter was considered for constructing the quasi-3D flow model. Determining the cell dimensions to study an aquifer is strongly dependent on the available information regarding the aquifer, its area, and the purpose of the study. Therefore, a 6-year period (2010-2015) was selected for simulating the model: four years (2010-2013) for calibration and two for verification. The monthly time step beginning fall 2010 was selected for simulating the steady state of the model since the least variation in water level and the lowest sensitivity of the aquifer to sources of discharge and recharge and to the available data happen at that time. Naturally, selection of the time step and of the first time step must be such that the aquifer is close to the steady state.

The groundwater level in early spring and in early fall (or late summer) reaches its highest and lowest levels, respectively, and, at the same time, has an almost steady state for a short time. The advantage of selecting the beginning of autumn as the steady state is that in previous months there is considerable rainfall and water extraction from the aquifer also decreases and, consequently, the model is influenced by unsteady conditions. Therefore, calibration in spring is relatively more difficult and more time-consuming since at that time there are a larger number of factors influencing aquifer discharge and recharge. However, these conditions make it possible to calibrate a larger number of variables. The available data and information can also influence the selection of the first time step. Actually, the steady state model indicates the first time step in modeling at which time, based on equations of groundwater flow, the hydraulic conductivity parameter must be calibrated.

After creating the grid, the geometric structure of the aquifer including topography and bedrock was entered into the mathematical model by using interpolation methods. The groundwater level in the first fall month 2011 was entered into the conceptual model as the initial condition. Figure (4) presents a view of the aquifer structure in the MODFLOW mathematical model.



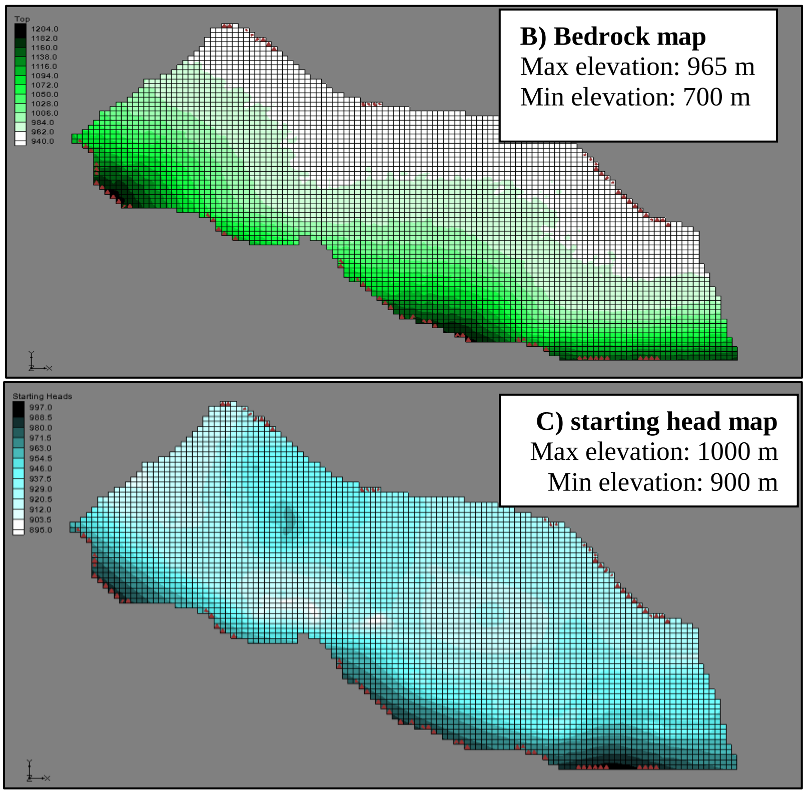


Fig 4. Structure of aquifer in the conceptual model

Based on the extracted results, the initial values for hydraulic conductivity were applied to the conceptual model as coverage using the Horizontal format K. On the basis of the latest report on groundwater resources balance, the discharge and recharge parameters of the aquifer including discharge from exploitation wells, rainfall penetration, runoff penetration, return flow from consumption, and transition water into the aquifer range was entered into the model. Average annual rainfall in the Plain region is 80.3mm (equivalent to 21million m^3 of water penetrating into the aquifer). Moreover, the annual penetration from the river into the aquifer is 1.6 million m^3. To determine the volume of return flows, it is assumed that 60-70% of the water allocated for drinking and for the industry sector and 20-40% of the water allocated to the agriculture sector reenters the aquifer. Considering the groundwater flow network and the equipotential lines, the inlet and outlet of groundwater into and out of the Ardestan aquifer were determined and the information was entered into the model as points using the coverage format of water masses with constant general head package (GHB). Figure (5) presents a conceptual model of the aquifer that shows all the input and output parameters.

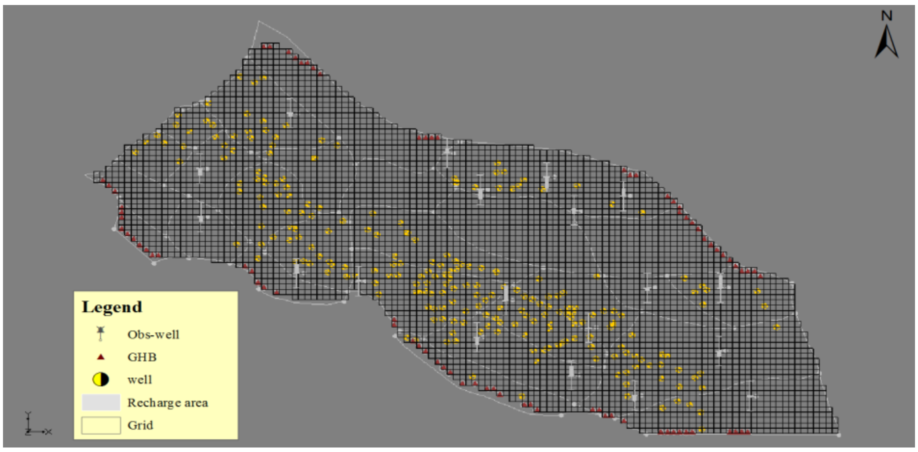


Fig 5. Conceptual model in Ardestan aquifer

Evaluation of model

After simulating the groundwater flow in the steady state, the difference between the inflows and outflows of the aquifer must be zero. To correctly and accurately run the steady state model in the Ardestan aquifer, the model evaluation was performed in the calibration stage. Calibration of the steady-state model of the groundwater consists of correcting the values of the hydrodynamic and sensitive parameters in the aquifer until the difference between the simulated and the measured groundwater levels is minimized. Following calibration of the steady-state model, simulation of groundwater flow in the non-steady state is performed. The model must be calibrated and verified to evaluate it in the non-steady state.

All stages of calibration both in the steady and non-steady states are carried out to obtain the least amount of error between the calculated measured water level in each observation well. Analysis of residual errors and of differences between calculated and observed values for hydraulic heights is carried out using different methods and employing various criteria.

a. Mean error: Mean error (ME) is expressed in the following relation. Although it is rarely used for analyzing the degrees of model accuracy and sensitivity, it is not a complete criterion as the presence of positive and negative errors in an algebraic sum can tend to zero:

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i \quad (2)$$

Here, n is the number of observations, h_m the observed hydraulic height, and h_s the calculated hydraulic height.

b. Mean absolute error: The following relation is employed to determine mean absolute error (MAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i \quad (3)$$

c. Root mean square: This criterion is defined in Relation (4):

$$RMS=\left[\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i^2\right]^{0.5} \quad (4)$$

In the calibration stage, the trial and error method and the automatic calibration software Parameter Estimation (PEST) were employed. Following calibration of the quantitative model in the non-steady state, verification of the quantitative model of the aquifer was performed to match the results and to evaluate accurately.

A model that is developed for the first time, especially if based on information and statistics of one specific year and/or of a very limited period, is not completely accurate, in most cases exhibits differences with the actual facts, and requires confirmation by previous information and statistics before it is used for predicting the future. Therefore, it is necessary to correct the initial data, which lead to the calibration of the model, when developing a model. Consequently, one of the requirements of a suitable model is to control and study its behavior against the interpretations and information of the last time to see if the observed results and the answers provided by the model sufficiently match. The length of time needed to match the results for verification depends on two factors:

a. The type of aquifer because each aquifer has a natural reaction time. For example, a free or semi-confined aquifer may be influenced by a single drought for many decades, whereas in a perfectly confined aquifer this influence will disappear within several years.

b. The past history, or the historical period, of the aquifer during which many varied behaviors and conditions governed the aquifer.

4. Results

There is usually uncertainty regarding the values of input parameters of a model because they are not specified and knowledge of the processes governing the regional hydraulic system is insufficient. The importance and effects of each of these parameters one on simulation results can be evaluated using sensitivity analysis. The value of each parameter is thus adjusted during several stages to values higher or lower than the calibrated one, and the magnitude of the changes that are made in the error levels are determined by re-running the model. The stages in model sensitivity analysis were as follows:

a. The input data together with their uncertainty ranges (evaluated during model calibration) were determined.

b.The model for flow calibration was run again in the determined ranges of the various input data, and every parametric value and water stress was individually changed in each stage of the sensitivity analysis.

c.The sensitivity analysis was reported in terms of the effects of parametric changes on the RMS error of the hydraulic load and represented by diagrams showing results of the sensitivity analysis.

Calibration of a model must have a predetermined and acceptable error rate. The acceptable error range depends on the goal for which the model is developed. In developing the model for the Ardestan aquifer, one meter was considered 1% error. The purpose in calibration is to minimize the error or the calibration criterion. Calibration of the model for the study region began after creating the model based on the following assumptions:

- Physical conditions of the aquifer like surface topography and bedrock do not change.
- Bedrock is impermeable throughout the region covered by the model.
- The volume of water extracted from exploitation wells remains constant.
- A free aquifer exists in the region.
- Hydraulic conductivity has a high uncertainty level.

The sensitivity analysis of the quantitative model in the steady and non-steady states suggested that there was sensitivity to hydraulic conductivity and specific yield. Previous research indicated that this was also the case in modeling. Taking the conceptual model for the aquifer into account and considering the groundwater resources balance in the Ardestan aquifer, the model was calibrated. Figure (6) shows the results of calibrating hydraulic conductivity in the aquifer. Part (a) indicates the value of the initial hydraulic conductivity in modeling determined based on pumping experiments and previous research, and part (b) presents the final results of calibrating hydraulic conductivity.

The steady state model of groundwater was calibrated by changing the values for hydraulic conductivity in a way that the least possible amount of error was observed between the observed and simulated groundwater levels. The basis for calibration error during the modeling period was the difference of less than 1% in the observed and simulated water levels (the total error of the model was less than 1%).

Results of error analysis suggest that the model enjoyed suitable accuracy for modeling the steady state. These results indicate that the RMS (that is, the difference between the observed and simulated groundwater level) in all 17 piezometers of the model is less than 50cm. Analysis of the groundwater level in the steady state showed in the table (1). Figure (7) shows the final model for the steady state of groundwater flow in the Ardestan aquifer. The results of the simulation in mod-flow show that in the central parts of the aquifer, the iso-piece of the groundwater level is closed, which indicates the depth of the quaternary and the saturation zone. This area has the potential for exploitation and changes in the groundwater level constant.

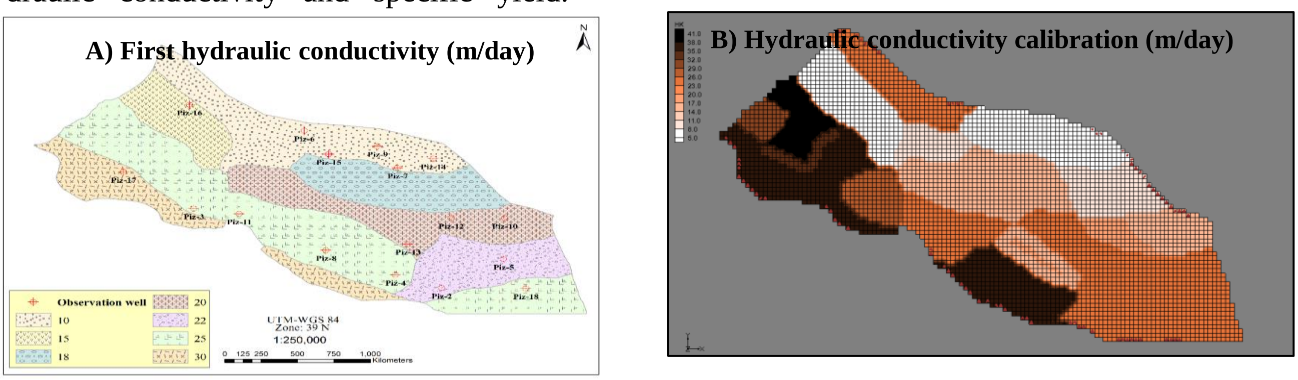


Fig 6. Hydraulic conductivity in Ardestan aquifer

Table 1. Analysis of groundwater level in steady state

Obs-well	UTM X	UTM Y	Observation level	Simulation level	difference	Obs-well	UTM X	UTM Y	Observation level	Simulation level	difference
Piz-2	641810	3694801	939.5	939.1	-0.37	Piz-11	619555	3705486	916	916.1	0.10
Piz-3	614572	3706247	914.9	915.5	0.59	Piz-12	642864	3704864	931.4	931.2	-0.16
Piz-4	636731	3696701	933.3	933.9	0.59	Piz-13	638126	3701135	928.6	928.6	-0.01
Piz-5	648605	3698970	941.4	941.0	-0.37	Piz-14	640907	3713431	930.9	931.4	0.51
Piz-6	626710	3717460	934.8	935.1	0.31	Piz-15	629407	3714065	926.8	926.2	-0.62
Piz-7	636970	3712106	928.7	928.8	0.10	Piz-16	614105	3721209	943	942.8	-0.23
Piz-8	629101	3700257	931.5	931.0	-0.52	Piz-17	606850	3711506	923.6	923.2	-0.36
Piz-9	634757	3715207	931.5	930.7	-0.76	Piz-18	651071	3694737	947.4	947.3	-0.07
Piz-10	648750	3704855	931.6	932.4	0.84						

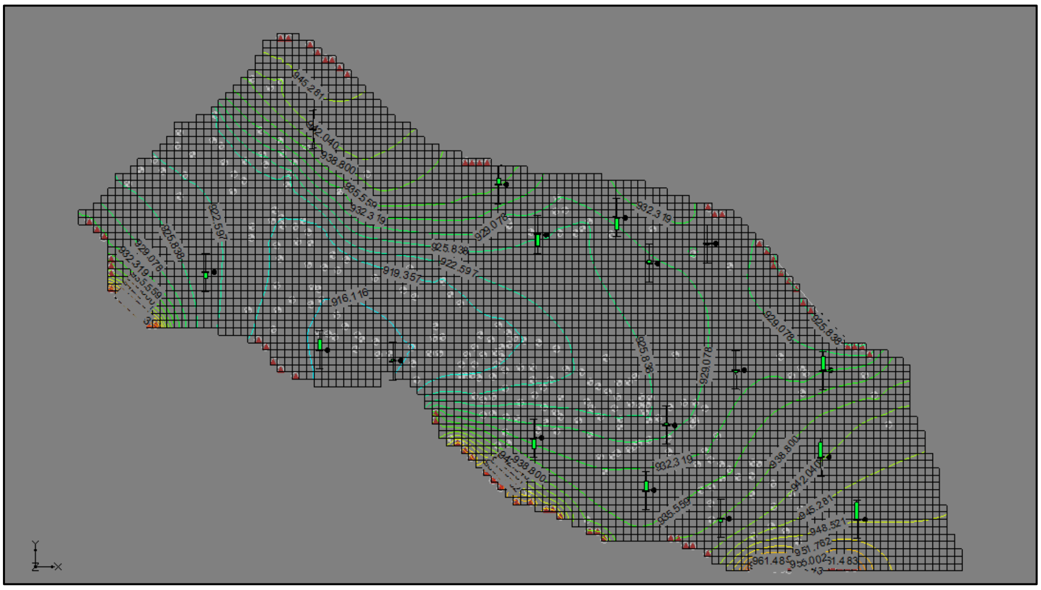


Fig 7. Steady model in Ardestan aquifer

To calibrate the model in the non-steady state, the trial and error method was used and the specific yield was considered the sensitive parameter in the calibration. It is preferred to carry out calibration in the non-steady state based on monthly values instead of daily or weekly ones because groundwater systems usually exhibit a delayed response to surface tensions. In addition, monthly data allow a correct analysis of seasonal effects, which is important in long-term predictions. Moreover, water extraction from observation wells is on a monthly scale. In this type of calibration, the purpose is to estimate specific yield (Sy) and, if needed, correct the hydrogeological parameters of the flow in the aquifer. The calibration of the non-steady state was carried out in parallel with the hydraulic conductivity parameter. Therefore, calibration in the non-steady state was performed by changing the values for storage coefficient and specific yield along with those for hydrogeological parameters. The basis for acceptability of the results was an amount of error similar to that for the steady state. Figure (8) presents the calibrated value for specific yield in the Ardestan aquifer. Table (2) shows the amounts of error for the steady and non-steady states in the Ardestan aquifer. The final model for the unsteady state of the aquifer is presented in Figure (9).

Table 2. Analysis of error in the steady and unsteady model

Error parameters	Steady model	Un-steady model
Mean Error	0.008	0.669
Mean Abs Error	0.418	1.031
RMSE	0.496	1.473

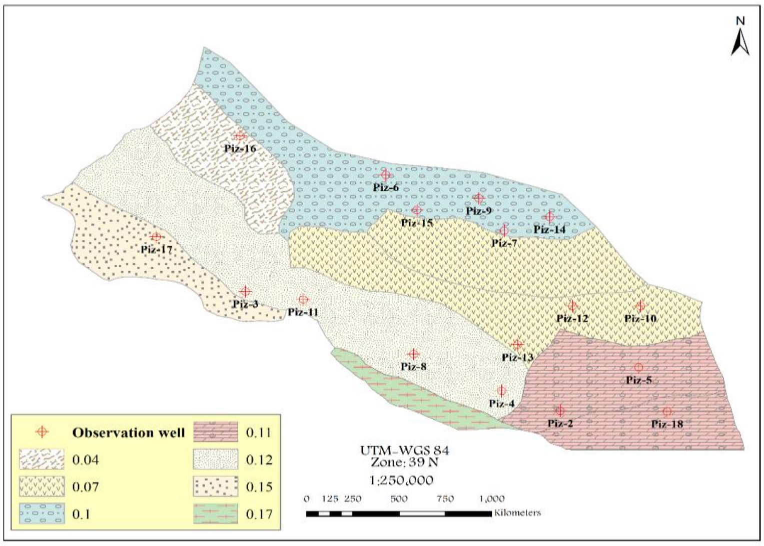


Fig 8. Specific yield in the Ardestan aquifer

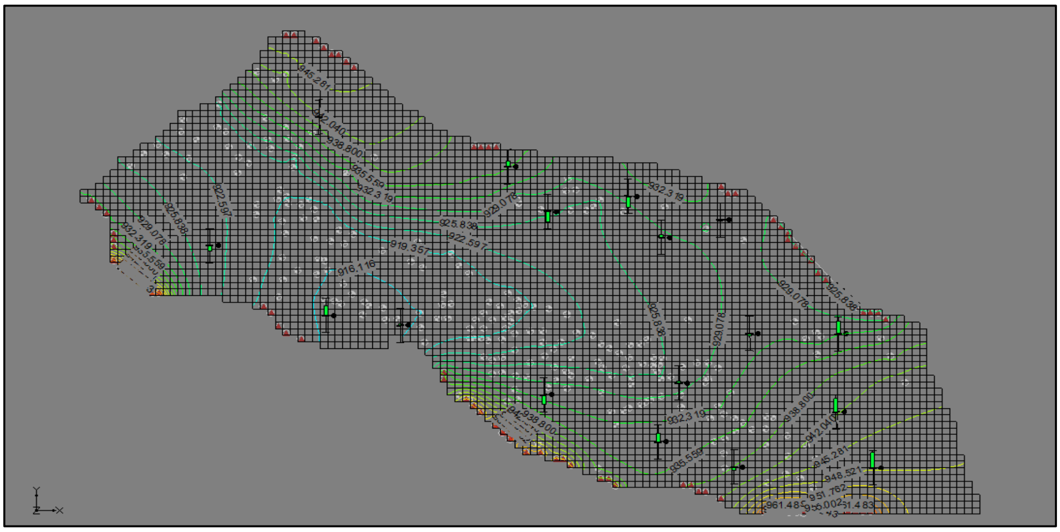


Fig 9. Un-steady model in Ardestan aquifer

One of the requirements of using a suitable model is to control and study model behavior against water extraction, and information obtained, in the past so that the observed results and those of the model sufficiently match. For this purpose, verification of the model for the non-steady state was carried out for the final two years to match the model. During this period, 24-time steps were analyzed. Figures (10) and (11) present the results obtained at the end of the fifth and sixth years of modeling that represent the observed groundwater level against the simulated one.

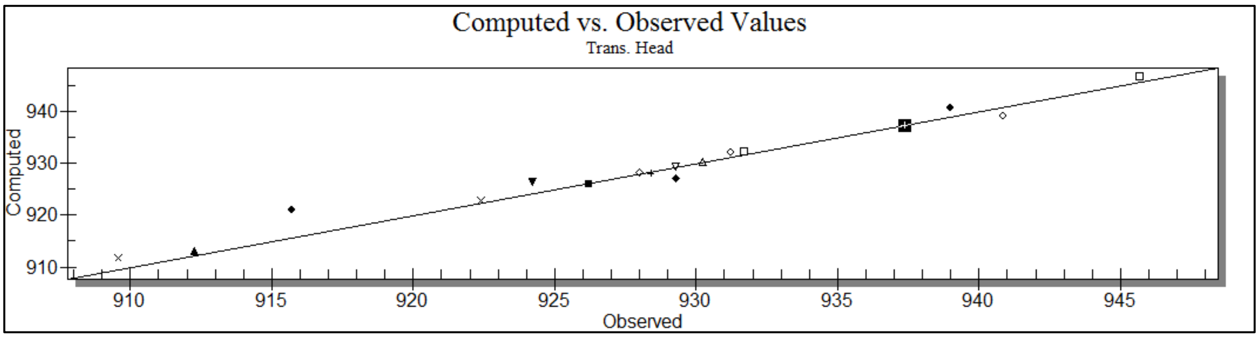


Fig 10. Correlation between observation and simulation level at the end of the fifth year of modeling

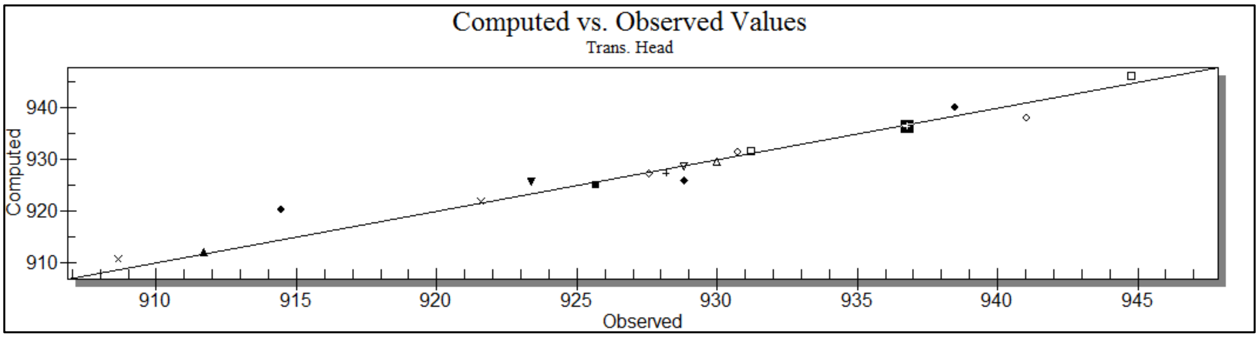


Fig 11. Correlation between observation and simulation level at the end of the sixth year of modeling

Verification results demonstrated that there was minimal difference between the observed and simulated water levels and all points were located around the baseline. Modeling results suggest that there was a decline in all the observation wells during the entire period. Figures (12-14) indicate simulated groundwater levels versus the observed ones for three observation wells in the aquifer. Results suggest the simulation was sufficiently accurate. In these X-axis diagrams, the time and axis represent Y groundwater levels. Accordingly, if the difference in observation and simulation levels of groundwater is within the permitted limits, it is displayed in green and in months with a large difference, yellow and red. These results are simulation outputs in the Moldflow model.

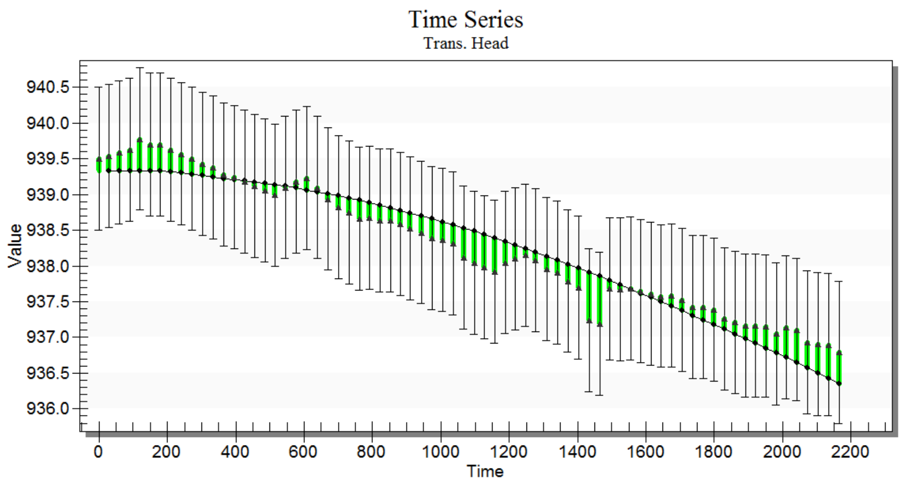


Fig 12. Correlation between observation and simulation level in observation number 2

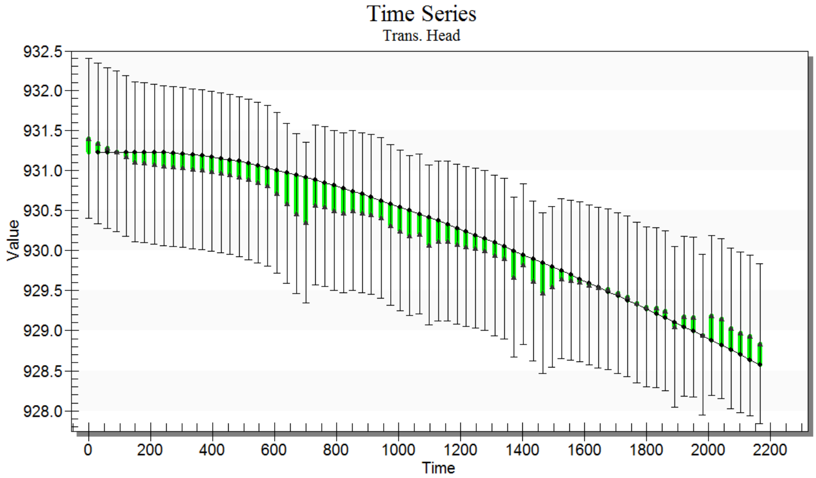


Fig 13. Correlation between observation and simulation level in observation number 12

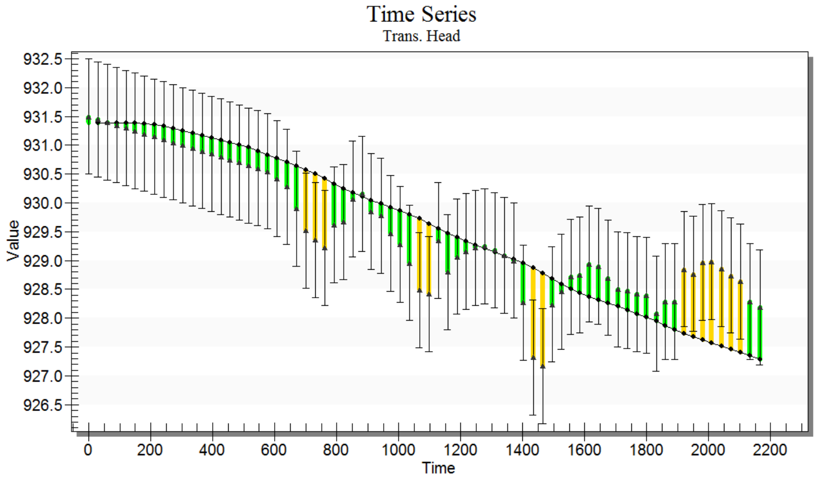


Fig 14. Correlation between observation and simulation level in observation number 14

5. Discussion

After modeling and simulating groundwater flow in the Ardestan aquifer, which is a dry aquifer connected to the desert, results of groundwater flow simulation showed that, in general, the direction of groundwater flow was from the southwest to the northeast of the aquifer according to results extracted from the observation wells. Furthermore, analysis of the water resources balance in this range suggested there was a negative balance so that the aquifer faced limitations with respect to exploitation. The two parameters of hydraulic conductivity and specific yield were introduced as the sensitive factors for the steady and non-steady state modeling and were calibrated using the trial and error method. Water level analysis of the 17 observation wells that were simulated also suggested a decline in the water level of the wells. The largest drop in water level was observed in the observation wells in the central section of the aquifer (P4, P8, P11, P12, and P13), whereas those in the beginning section of the aquifer exhibited the least drop in water level. Study of the groundwater flow network in the quantitative model indicated that these conditions were not observed in the outlet sections of the aquifer because of the negative aquifer balance and due to the general direction of the groundwater flow. Careful examination of the aquifer grid cells in the outlet section of the groundwater flow showed that in the northern parts of this region, where the water balance was more positive compared to the southern parts, the direction of groundwater flow was reversed. The study of boundary conditions in this section of aquifer shows the kind of fronts of type GHB, which has a fixed head characteristic. Time series analysis in the non-steady model shows that due to the drop in groundwater level due to overuse, the groundwater level of the outlet from the aquifer is not altered and this decrease leads to a reversal of the direction of flow and change in the hydraulic gradient. Considering the severe decline in the groundwater level, and the consequent reduction in aquifer hydraulic gradient, the volume of groundwater outflow decreased. This reduction in the obtained results was also evident in the water resources balance during the past 20 years so that the latest balance reports estimated that the annual outflow volume was less than 1 million m^3. The decline in the outflow from the aquifer toward the desert caused the water level in the desert part, where there is no water extraction and no drop in groundwater level, to be higher compared to the Ardestan aquifer. This led to saltwater encroachment in the aquifer from its outlet section. Analysis of this change in flow direction shows that the outlet section of the aquifer, which is connected to the desert aquifer with high salt content, will soon cause land salinization, the formation of salt marshes, and the emergence of environmental issues. Figure (15) presents the results of the aquifer outlet masses. In this section of the aquifer, the outlet masses turn into inlet masses and the groundwater flow enters the aquifer.

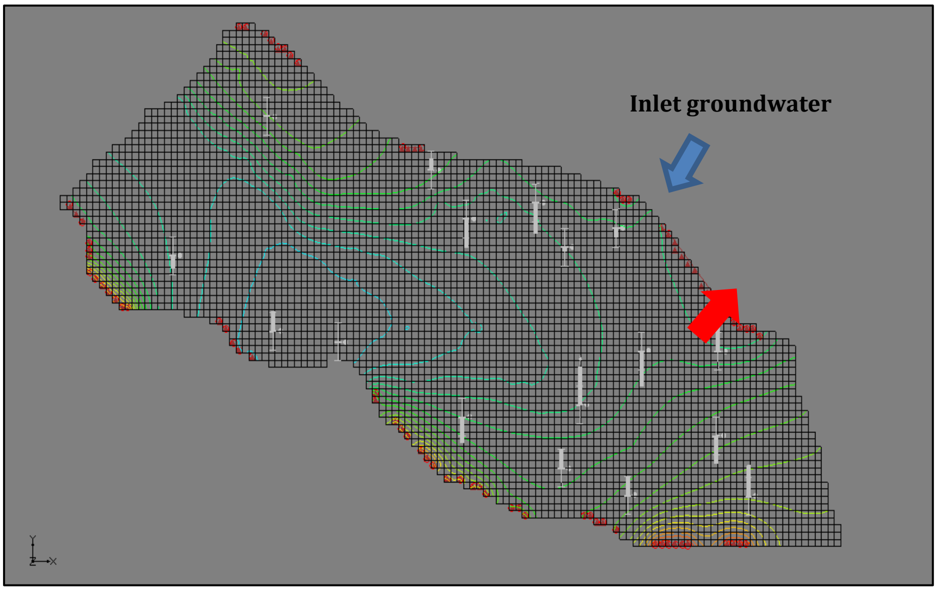


Fig 15. Change to inlet and outlet of groundwater

6. Conclusions

The present study employed a mathematical model to quantitatively model the Ardestan aquifer for sustainable management and to analyze the role desert aquifers played in the outlet section of this aquifer. The modeling was performed by considering the water resources balance and the latest national inventory of water resources and through selecting six water years (2010-2015) for simulation. The first four years were used for calibration and the final two for certification. After building the conceptual model and defining the input and output parameters, the simulation was performed for the steady-state and sensitivity analysis was carried out for careful evaluation of the model. Hydraulic conductivity was then determined as the sensitive parameter of calibration and calibrated using the trial and error method. Following stimulation of the steady state, simulation of the non-steady state was performed. After specific yield was identified as the sensitive parameter, it was calibrated and, finally, the model was verified. Analysis of the results obtained from the model indicated that the Ardestan aquifer had a negative balance and groundwater level decline in the aquifer was completely visible. The regional study of groundwater flow in the outlet section of the aquifer revealed that the direction of the groundwater flow had changed in this section. In the northern parts of this section, the direction of the groundwater flow had changed due to the drop in the groundwater level of the aquifer. The reversal of the hydraulic gradient due to the increased water level in the desert section compared to the aquifer outlet section caused water to transition from the aquifer outlet section to the aquifer. With respect to the simulation carried out to determine the salt zones, most studies have been carried out in coastal aquifers and simulations have been less analyzed in desert aquifers. Kardan Moghaddam and Bani Habib also predicted in the desert crater aquifer in 2017, after simulating the influx of saltwater fronts in the aquifer outlet. Their results were examined only on the basis of the current trend of harvesting under three scenarios. A careful study of this event using simulation of the quantitative model and investigation of the qualitative changes can demonstrate its environmental effects. Results of the present study indicate that uncontrolled water extraction reduces groundwater level in the aquifers and the quality of water resources, and has effects like land subsidence. However, desert freshwater aquifers that are connected to saltwater desert aquifers can also experience encroachment of saltwater.

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