Water Harvesting Research, 2016, 1(1): 52-62
www.jwhr.birjand.ac.ir
P-ISSN: 2476-6976, E-ISSN: 2476-7603
DOI: 10.22077/JWHR.2017.377

Management of groundwater resources of Mahvelat-Faizabad aquifer and evaluation of extent of saline water zone using numerical simulation

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Received: 14 April 2016 / Accepted: 27 June 2016

Abstract

The unmanaged groundwater extraction and inadequate aquifer recharge is the major cause of groundwater depletion in different parts of the world. In this study, the groundwater flow system of Mahvelat-Feizabad aquifer (NE of Iran) has been numerically simulated using MODFLOW code in the GMS interface. The model, primarily, calibrated for steady state condition for the mean hydraulic values of one-year period (Sep. 2012 to Sep. 2013) which has steady condition with low stresses on aquifer. Then the model is run/calibrated for transient condition for one year period (Sep. 2012 to Sep. 2013). After determining the hydraulic properties of the aquifer and confirming their validity, different scenarios were applied to the model. Results show that, by continuing the current aquifer conditions, there will be a constant decrease in water level with the approximate rate of 0.8 m/year. Changing the exploitation of water from critical zone and overexploitation from saline water zone will affect the critical zone by causing a sharp decline in water level as well as its affection in water quality parameters that directly affect the agriculture of this area. Results show that proper management of aquifer can affect the groundwater flow direction and extent of saline water zone. In addition, artificial recharge which contain direct and indirect technique such as percolation tank and injection well and spreading channel are all the preventative measures to overcome the expansion of saline water zone.

Keywords: *Simulation, MODFLOW, Mahvelat-Feizabad, Management, Groundwater Harvesting.*

1. Introduction

Water scarcity, in general, is due to the lack of resource management and due to changes in environmental factors. The usage of available resources in a sustainable way and appropriate groundwater management will help to meet the needs of the present era without compromising future generations. Since the early twentieth century, groundwater flow models, as powerful hydrogeological tools for monitoring, controlling, and managing groundwater resources, have been implemented worldwide in order to create a better understanding of the head distribution, identify flow patterns, and predict future hydrodynamics of aquifers. Numerical models defining groundwater flow systems are based on groundwater governing equation that combines Darcy's law and water mass balance (Carroll et al., 2008). The groundwater flow simulations are only based on parameters and properties of the aquifer, which can be performed through mathematical modelling (Yang et al., 2011).

In the past few years, there has been a rapid development in numerical models. These models require various geological and hydrogeological data to define aquifer boundary/initial conditions, hydraulic properties, and possible stresses to the system. In the last few decades, numerous studies have been conducted using professional groundwater software, such as: Visual MODFLOW, GMS, FEFLOW, and SEAWAT.

Miller (2000) studied the groundwater flow in an unconfined sand and gravel aquifer at Marathon in New York using MODFLOW numerical code. Laronne and Gvirtzman (2005), using MODFLOW code in the GMS interface, studied the groundwater flow along and across structural folding in the Judean desert in Israel. The same code was applied to simulate a transient groundwater flow model to investigate the influence of sanitation conditions on shallow groundwater in Kampala state, Uganda (Herzog, 2007). Wang and colleagues (2007), by combining MODFLOW and geographic information system (GIS), were able to simulate groundwater flow in northern China. Wels and Findlater (2009) applied a three-dimensional groundwater flow (MODFLOW) and solute transport model (MT3D) to predict timing and magnitude of peak zinc concentrations in a shallow groundwater discharge to the nearest stream in south Darwin, Australia. Yang et al. (2011), developed a groundwater flow model in Tongliao city of China using Visual MODFLOW to identify the aquifer properties and to analyze groundwater flow dynamics and changes of groundwater levels. Additionally, in recent decades several researchers have applied simulation techniques to study water table fluctuations and to simulate groundwater reservoirs in different parts of the world (Ebrahim, 2002; Karahan and Ayvaz, 2005; Shaki and Adeloye, 2007; Velazquez et al., 2007; Zheng and Mingzhu, 2007). Among simulation techniques, the GMS approach includes a comprehensive graphical interface to the groundwater model MODFLOW. MODFLOW is a three-dimensional, cell-centered, finite difference and saturated flow model developed by the United State Geological Survey (McDonald and Harbaugh, 1988). MODFLOW can perform both steady state and transient analysis and has a wide variety of boundary conditions and input options. MODFLOW2000, the new version of MODFLOW, is a significantly enhanced version of the U.S. Geological Survey (USGS) modular finite difference groundwater flow model (Harbaugh et al., 2000).

Due to water shortages in large areas of Iran, water resources management is of great importance. Over exploitation of groundwater resources in Mahvelat-Feizabad plain has decreased the water quality parameters that directly affect the agriculture of this area. Furthermore, the development of Mahvelat-Feizabad plain in agriculture, industry, and services are correlated with the development of sustainable exploitation of water resources. Management practices such as use of water resources modelling play a major role in avoiding the adverse effects of the exploitation of groundwater resources. In this regard, mathematical simulation of Mahvelat plain was performed.

2. Materials and Methods

2.1. Geology and hydrogeology of the area

From a geological point of view, Mahvelat-Feizabad catchment, with an area of approximately 2145 km^2, is located in the east of central Kavir basin (NE Iran) and in central Iran. The Mahvelat-Feizabad basin, with a height of about 1300m, is also placed between 57˚58′ E to 59˚03′ E longitudes and 34˚48′ N to 35˚11′ N latitudes (fig.1).

The climate is arid and semiarid, with a mean annual temperature of 17.4ºC and an average annual rainfall of 154 mm. Precipitation, which mainly occurs during winter and spring, is unevenly distributed in space and time and there are no rivers with permanent flows in this area. As mentioned before, the Mahvelat-Feizabad basin is located central Iran. The oldest geological units, which have outcrop in the area, belong to the Kalshaneh formation (Cambrian) and the newest one is Quaternary sediments in the central parts of the plain. The Mahvelat-Feizabad aquifer is an unconfined aquifer surrounded by mountains. The minimum and maximum thickness of the alluvial aquifer, which varies from 60 to 200 meters, are located in southeastern and central parts of the aquifer, respectively.

In this alluvial aquifer, transmissivity (T) varies between from 990 m2/d to 1085 m2/d, depending on spatial location, whereas, the average specific yield (Sy) is about 0.06. Groundwater flow direction is, in general, from south, east, and west to the north and the central parts. The depth of the water table expands from south and northwest to north and northeast of the aquifer. In General, it can be concluded from hydrogeological map assessment that water table has more than 10 meter depth in all parts of the aquifer and evapotranspiration is consequently improbable. Most of the 291 exploitation wells are located in central parts of Mahvelat-Feizabad aquifer. According to water quality data, there is a zone in the western part of the aquifer with salinity range higher than the average of the aquifer.

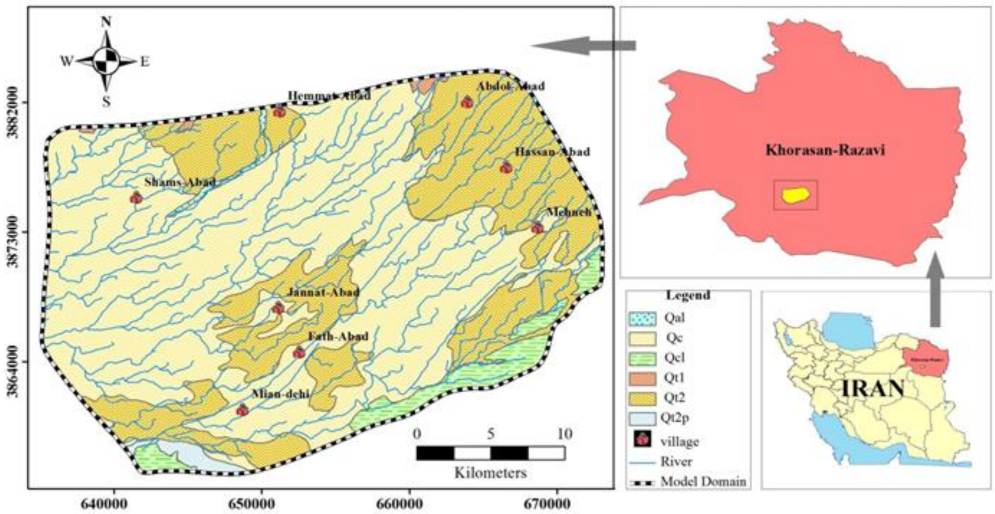

Fig. 1. Location and geological sketch of Mahvelat-Feizabad plain catchment area

2.2. Conceptual model and water budget

The sources of water to the system as well as the expected flow directions and exit points are the base of the conceptual model (Anderson and Woessner, 1992). Water budget, the overall sum of inputs and outputs in a hydrogeological system, is an essential part of the conceptual model (Andersen and Woessner, 1992). Water budget calculations are based on collected required data (such as annual precipitation, temperature, evaporation, groundwater levels, and runoff) for the Mahvelat-Feizabad aquifer's catchment area. Calculated net recharge is defined as the sum of induced recharge by irrigation (average of 15%), infiltrated runoff subsequent to rainfall events (average of 5%). The total groundwater recharge (125.23 MCM/year) and discharge (152.33 MCM/year) were calculated by applying

Darcy's law and transmissivity data of the aquifer. Exploitation of water resources (such as wells) constitutes the greatest part of the groundwater discharge (115.33 MCM/year).

After gathering the required data, aquifer conceptual model was prepared using Block Centered Flow (BCF) package. Data from 26 observation points were imported to the model using observation coverage ability in GMS interface. Other layers include sources and sinks, distributed recharge, and hydraulic parameters, which were defined using the relevant packages. An approximate study area of 805 km^2 and a single vertical layer was used for model conceptualization.

2.3. Numerical model setting

The numerical groundwater flow simulations of Mahvelat-Feizabad aquifer were conducted using MODFLOW code (Harbaugh et al., 2000), with the GMS pre-post processors. The study area has been discrete to 56 rows and 77 columns, with dimensions of 500×500 meters using construction finite difference grid. Top and bottom layers elevations of the shallow aquifer were derived from topographical maps, provided by Khorasan-Razavi Regional Water Authority. As mentioned earlier, the groundwater flow direction is, in general, from south, east, and west (groundwater inflow boundaries) to the north and the central parts. Therefore, general head boundaries were assigned for all over aquifer boundaries in the model domain. There is no permanent river within the model domain.

2.4. Steady state calibration

After converting the conceptual model into the grid cells, the numerical model was executed for steady state conditions. The average values of 12 water levels' measurements, for one-year period data from Sep. 2012 to Sep. 2013, were applied for steady state calibration. The purpose of calibration is to establish that the model can reproduce field-measured heads and flows. During calibration, a set of values for aquifer parameters and stresses was observed which approximates field-measured heads and flows. The necessity to calibrate the model originates from the uncertainty in parameter values due to the number of assumptions and simplifications made in the conceptual and the mathematical models (Carey et al., 2001).

Calibration was conducted through troublesome trial and error by changing aquifer hydraulic parameters, recharge rates, and comparing calculated head to those measured in observation points, as well as, comparing calculated fluxes across the boundary to those derived using Darcy's law in water budget section.

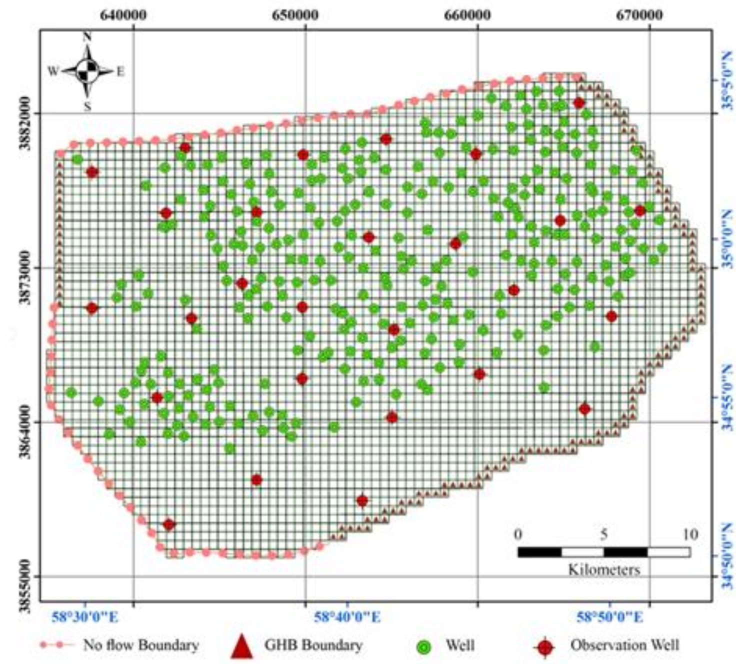

Fig. 2. Boundary conditions type, model grid, and water resources

Best fit was obtained when the residuals between calculated and observed heads were reduced to the defined tolerance of ±1 m. Figure 5a and 5b show the best fit between calculated and observed head in the last execution model and the final statistic errors, respectively. These results were achieved when the studied area was divided into regions having different hydraulic conductivity (K) varying from 3 to 12 m/d.

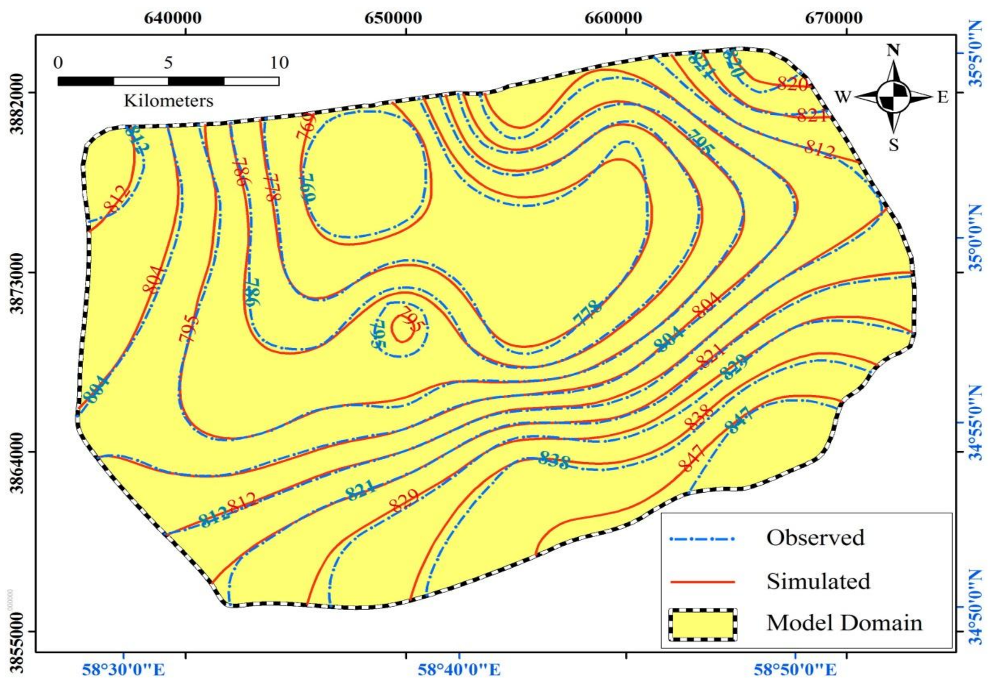

Fig. 3. a) Observed and simulated head contours (values in meter)

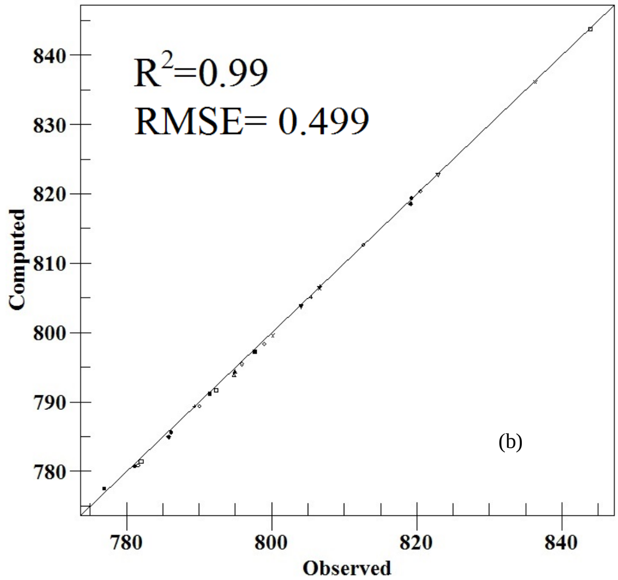

Fig. 3. b) Computed Value vs. Observed Value in Steady State

2.5. Transient calibration and verification

Proper simulation required smaller cell size and time steps to display spatial and temporal changes in hydraulic head, respectively (Spitz & Moreno, 1996). Time discretization in the constructed MODFLOW model were started from sep.2012 to sep.2013, with stress and time step of one month (30 days).

In the transient conditions, data such as: pumping rate, boundary head, recharge from rainfall, and return flow were entered into the model proportional to the stress period lengths and used starting heads of the solution generated from steady state model. The calibration of transient model was carried out based on groundwater hydrograph data from 26 observation wells (Fig. 4). This stage was performed by trial and error adjustments of hydraulic parameters such as Sy and K to achieve best fit between observed and calculated heads. Finally, once the transient calibration was performed with ranging of Sy from 3 to 6%, transient validation simulation was performed for 12 months transient period from Sep. 2013 to Sep. 2014. The purpose of model verification is to establish greater confidence in the model by using the set of calibrated parameter values and stresses to reproduce a second set of field data (Anderson & Woessner, 1992). Optimization and confirmation of the accuracy of the aquifer hydraulic parameters were performed according to the result of the observational water budget. In fact, the model must be able to simulate in/out fluxes, with acceptable approximation to values calculated in water budget based on measured field data.

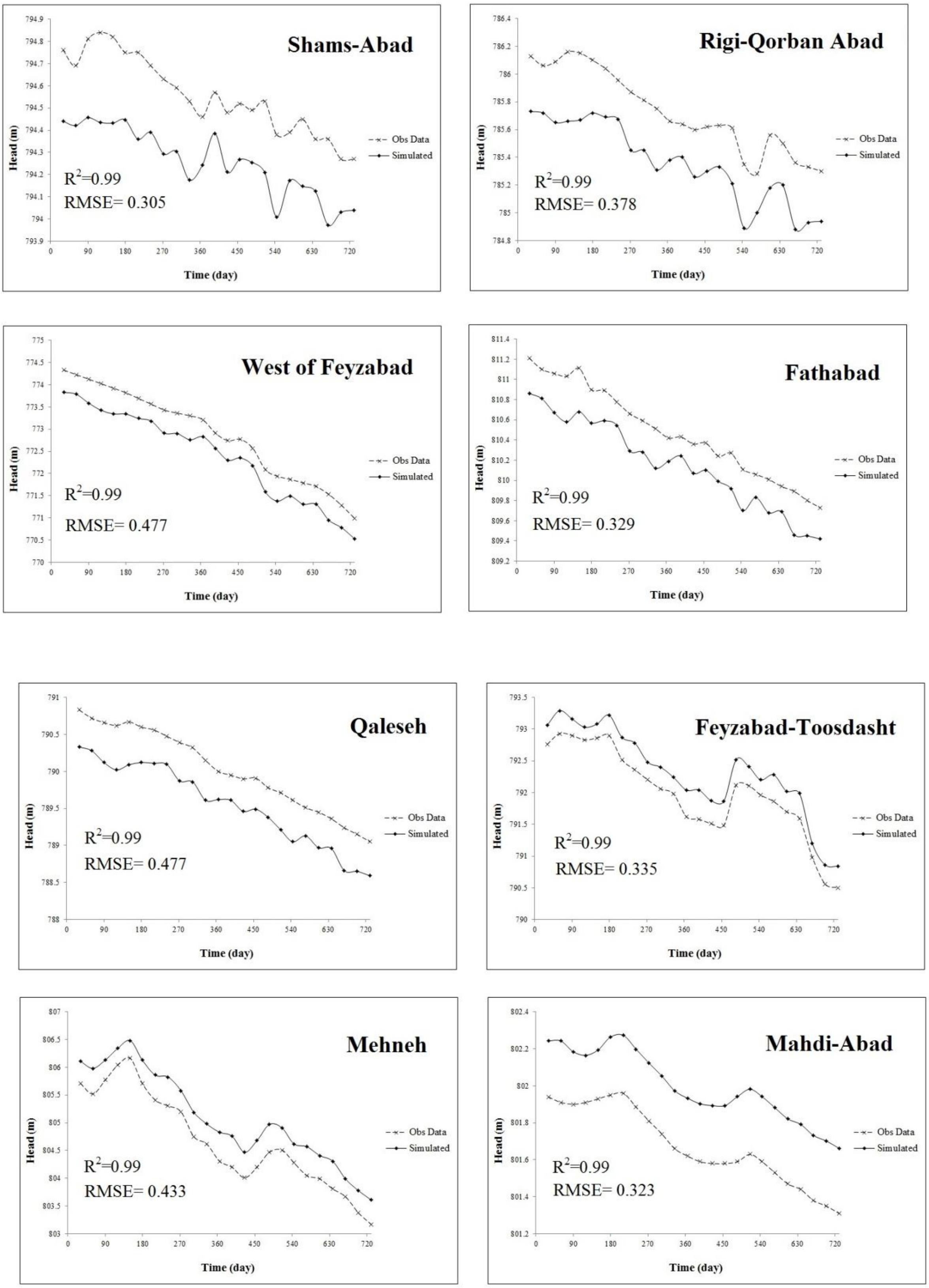

Fig. 4. Measured and simulated hydraulic heads of transient model

3. Results

Once the model was confirmed in the verification step, future aquifer conditions can be predicted for different management scenarios. The most important goal of groundwater modelling in Feizabad-Mahvelat aquifer is to study the strategies and respond to different management scenarios such as quantitative assessment scenarios in order to change the rate of exploitation as well as the scenarios for controlling the saline water zone in the study area.

Scenario 1- Predicting the groundwater condition for the next 4 years

In this scenario, the model was executed for a period of four years, from Sep.2014 to Sep.2017. The results of numerical modelling in this scenario include the simulated groundwater level for Sep.2017. which is illustrated in fig. 5. Assuming the continuation of current conditions, evaluation of groundwater level in this period showed a further decline in water level in central and northern part of the aquifer and critical zone, compared to other areas. This result also corresponds to hydrogeological facts. Due to the large number of wells in the critical zone and decrease of water levels, hydraulic gradient was high in this area which induces more freshwater to agricultural wells.

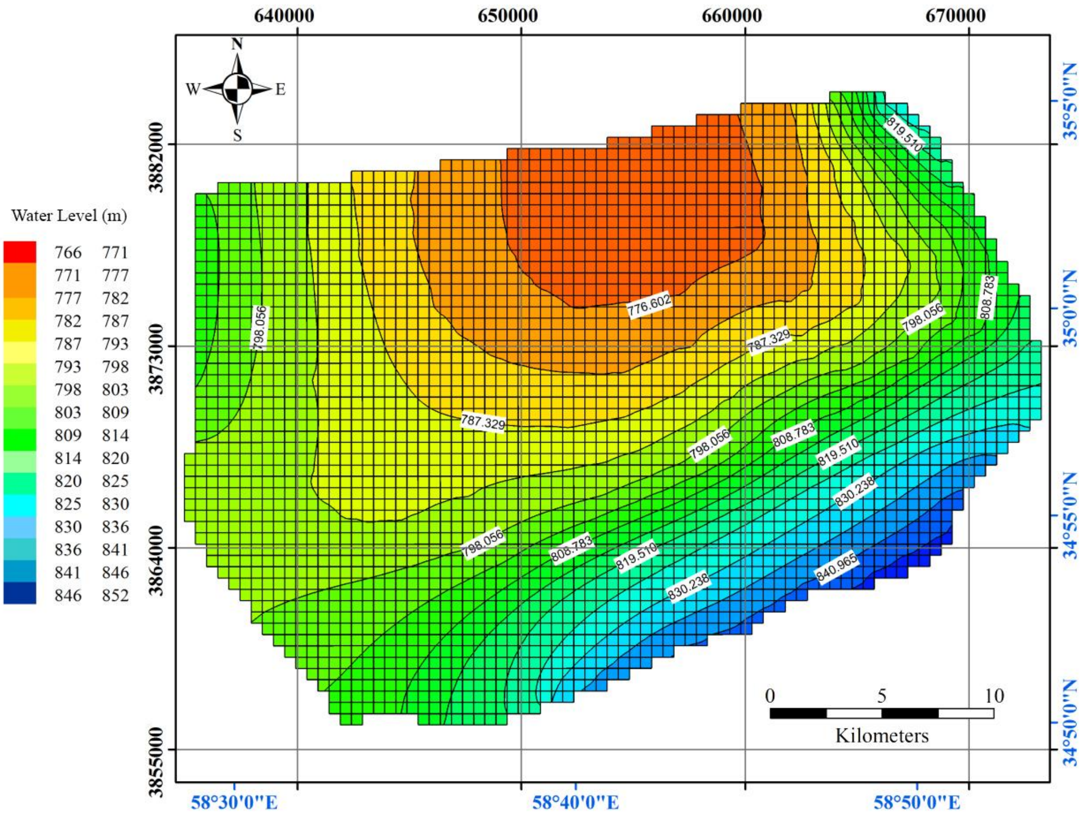

Fig. 5. Simulated groundwater levels in Sep.2017

Scenario 2- Changing the exploitation of water from critical zone and overexploitation from saline water zone

Saline water zone was determined using qualitative data. Considering changes in water table affecting the saline water zone orientation, the numerical simulation of aquifer was developed. Attempts were also made to develop an exploitation plan on the aquifer. In order to assess the effect of changes in water exploitation from critical zone and evaluation of the effect of excessive water extraction from saline water zone simultaneously, water extraction in critical zone was reduced by 30 percent and rate of water exploitation form saline zone was increased as much as 3.18 MCM/year. Results of imposing these conditions to the model for Sep.2017 are depicted in fig. 6.

In order to evaluate and monitor the changes of saline water zone, 10 wells with total exploitation of 4.4 MCM/year (approximately equal to one third of the induced recharge by irrigation) were added to western part of the aquifer. Calculated water levels at the end of the simulation period (Sep.2017) are illustrated in fig. 7

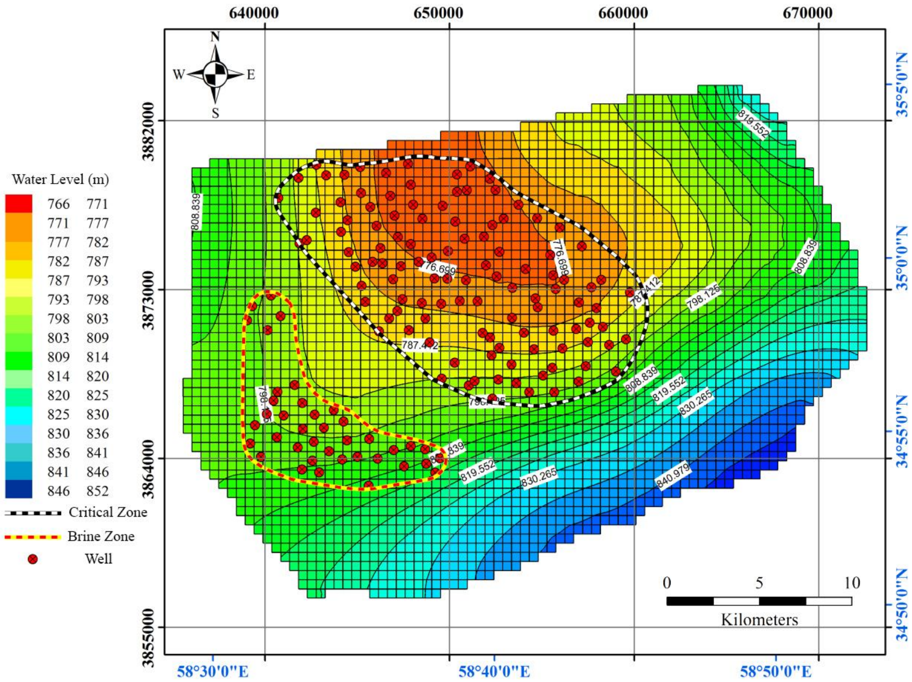

Fig. 6. Simulated groundwater levels with changing the exploitation of water from critical zone and overexploitation from saline water zone (Sep.2017)

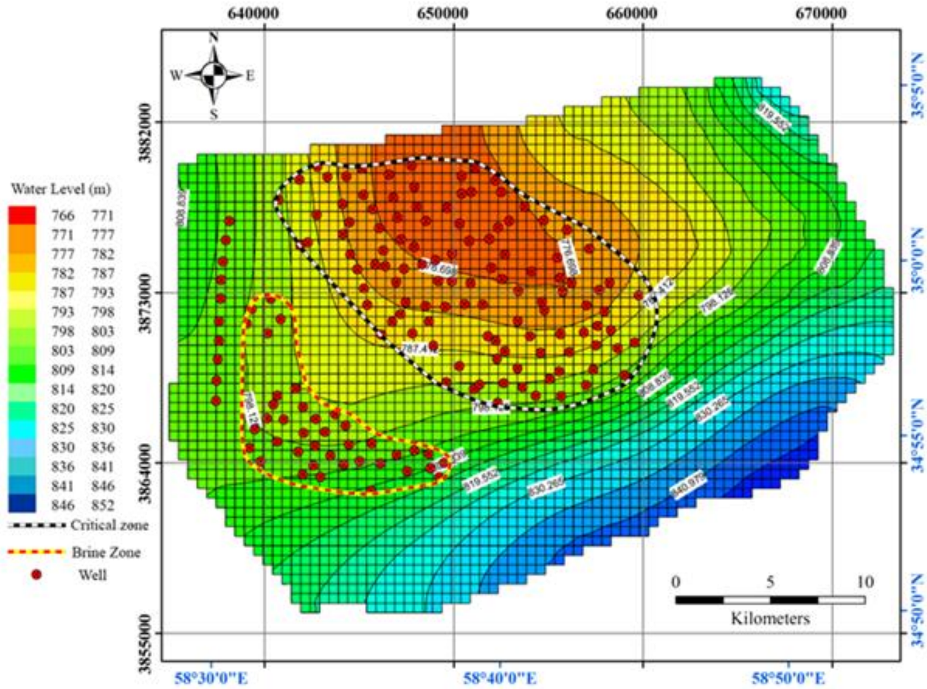

Fig. 7. Simulated groundwater levels, assuming 10 additional wells (Sep.2017)

4. Discussion and Conclusion

In this study, groundwater flow system of the Feizabad-Mahvelat aquifer, has been simulated using MODFLOW code in GMS interface. By running the Feizabad-Mahvelat model, it can be concluded that the aquifer has high sensitivity to well exploitation in addition to hydraulic conductivity. Results show that hydraulic conductivity varies between 3 to 12 m/d and Sy has the range of 3 to 6%. In addition, the future aquifer conditions have been predicted by applying different management scenarios to the aquifer: 1) Predicting groundwater condition for the next 4 years. 2) Changing exploitation of water from critical zone and overexploitation from saline water zone. Results show that by continuing the current condition, there will be a constant decrease in water level with an approximate rate of 0.8 m/year. Most changes will occur in central and western parts of the aquifer. By applying the second scenario and by the course of time, the sharp decline in water level was simulated in critical zone at the end of simulation period so that the reduction zone is oriented towards the west. The reason for this can be related to the focus of wells in this area. By adding 10 wells with a total exploitation of 4.4 MCM/year, the trend of water reduction will be changed. All of the above confirm that artificial recharge, which contains direct and indirect techniques such as percolation tank and injection well and spreading channel are all preventative measures to overcome the expansion of saline water zone.

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