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WATER RESOURCES AND THE REGIME OF WATER BODIES

Prediction of the Effect of Water Supplying from Shirindare Dam on the Bojnourd Aquifer Using MODFLOW2000[1]

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Abstract—In recent years, the water demand has been increasing considerably in Bojnourd, capital of Northern Khorasan province in NE of Iran, and the extracted water from Bojnourd alluvial aquifer, with an area of 65 km^2, is not sufficient for residents. The required water is going to be supplied from Shirindare dam, located out of Bojnourd aquifer's catchment area; therefore, the groundwater levels will rise in some parts of the aquifer, due to the return flow of supplied water, which will cause serious problems for the city. In this paper, the groundwater flow system of Bojnourd aquifer has been numerically simulated using MODFLOW code in GMS interface. The model, primarily, was calibrated for a steady state condition for the mean values of one-year period (Sep. 2009 to Sep. 2010) which has a steady condition with low stresses on the aquifer. Then the model was run/calibrated for transient conditions for a two year period (Sep. 2007 to Sep. 2009). After determining the hydraulic properties of the aquifer and confirming their validity, different management scenarios, were applied to the model. Results reveal that groundwater levels in the urban area will rise by over 3 m, by infiltrating 40% of supplied water from the Shirindare dam into the aquifer. To manage the rising water levels, two different management scenarios were applied to the aquifer model. In doing so and with proper management of aquifer exploitation during critical situations, not only will the groundwater level drop; also the city of Bojnourd can develop urban landscaping by constructing sports/cultural camping area using the extra pumped water.

Keywords: Bojnourd aquifer, Shirindare dam, MODFLOW2000, prediction

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INTRODUCTION

Since the early XX century, the groundwater flow models, as a powerful hydrogeological tool for monitoring, controlling and managing groundwater resources, have been implemented worldwide to comprehend 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 [4]. The groundwater flow simulation is based on considering only parameters and properties of the aquifer, which is possible through mathematical modeling [22].

In the past few years, there has been a rapid development of numerical models. These models require various geological and hydrogeological data to define the aquifer boundary/initial conditions, hydraulic properties, and possible stresses on the system. In the last few decades, the numerous studies have been conducted using some professional pieces of groundwater software, such as: Visual MODFLOW, GMS, FEFLOW, SEAWAT. Miller [15] studied the groundwater flow in an unconfined sandy and gravely aquifer at Marathon in New York using MODFLOW numerical code. Laronne and Gvirtzman [11] used MODFLOW code in the GMS interface and 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 the sanitary conditions of shallow groundwater in Kampala state in Uganda [9]. Wang et al. [20], with combining MODFLOW and geographic information system (GIS), were able to simulate groundwater flow in northern China. Wels and Findlater [21], applied a three-

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dimensional groundwater flow (MODFLOW) and a solute transport model (MT3D) to predict the timing and magnitude of peak zinc concentrations in a shallow groundwater discharging to the nearest stream in south Darwin, Australia. Yang et al. [22], developed a groundwater flow model in Tongliao city, China by using Visual MODFLOW to identify the aquifer properties and to analyze groundwater flow dynamics and changes of groundwater level. In addition, in recent decades, several researchers have applied simulation techniques to study the water table fluctuations and to simulate the groundwater reservoirs in different part of the world [5, 8, 10, 16, 19, 23]. Among all these simulation techniques, GMS includes a comprehensive graphical interface with the notorious groundwater model MODFLOW. MODFLOW is a three-dimensional, cell-centered, finite difference and saturated flow model developed by the United States Geological Survey [14] and it can perform both steady state and transient analyses 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 [7]. In recent years due to city sprawl of Bojnourd, capital of Northern Khorasan province in NE of Iran, the water demand has been considerably increased. Therefore, the extracted water from exploration wells is not sufficient; consequently, the required extra water must be supplied from other sources, e.g., Shirindare dam, which has high quality water and is located out of Bojnourd aquifer's catchment area. The groundwater level within Bojnourd aquifer is relatively high and depth of water table in some parts of the aquifer is less than 4 m. Therefore, the return flow of supply water from Shirindare dam will rise most probably the groundwater level even higher than the ground surface in some parts of the aquifer, which will lead to serious problems for the inhabitants. In this paper the groundwater flow system of the aquifer has been simulated using MODFLOW code in GMS interface. In addition, the simulated model has been applied as a tool to predict the future conditions of the aquifer for the different management scenarios, such as transferring about 20 (MCM) water annually from Shirindare dam to Bojnourd aquifer.

STUDY AREA

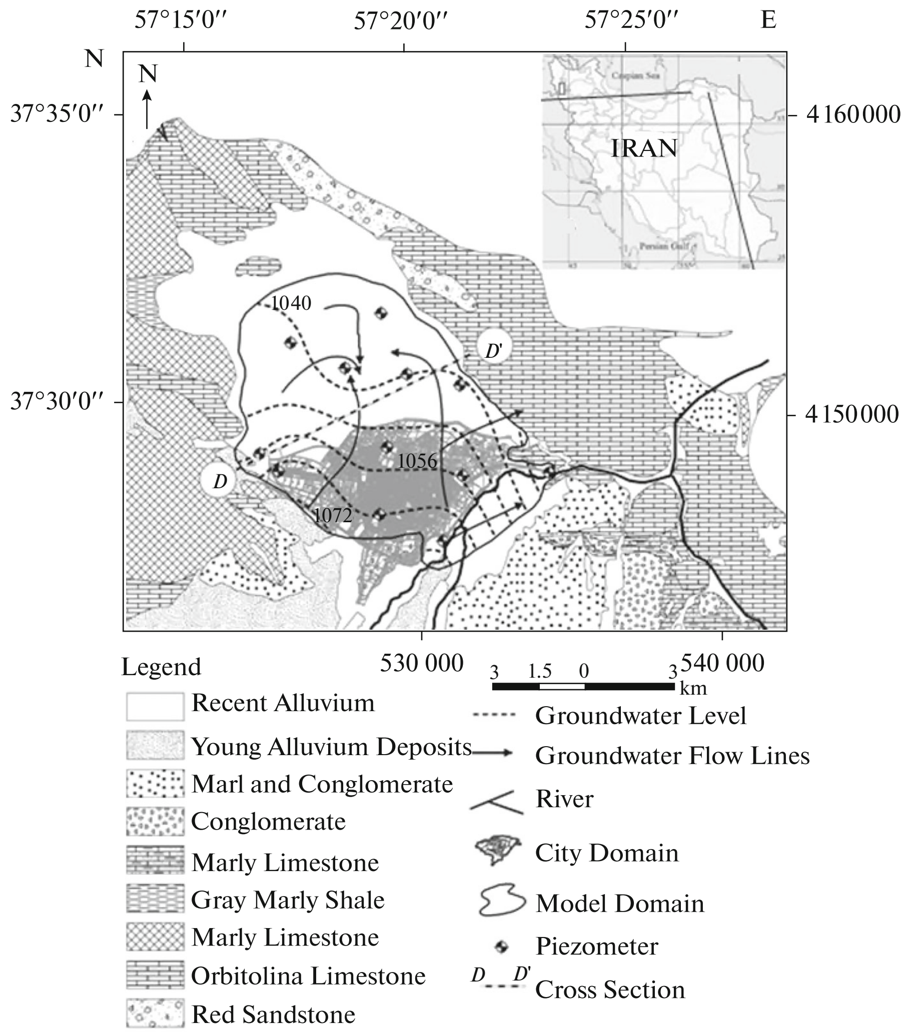
The Bojnourd catchment extends over an area of about 1280 km^2 in the center of North Khorasan province (NE Iran; Fig. 1a). Mountainous covers about 1033 km^2 of the Bojnourd plain, with a high and average altitudes of 2900 and 1625 m above sea level **(masl)**, respectively. The plain area of the basin is about 247 km^2, with a low and average altitudes 920 and 1175 masl, respectively. Bojnourd, with a height of 1075 masl and extend of 28 km^2, is located in the south of the main plain of the basin with an area of 90 km^2. The climate is semiarid, with a mean annual temperature of 9.8°C and an average annual rainfall of 292 mm [13]. Precipitation, which mainly occurs during winter and spring, is unevenly distributed in a space and time. The only outflow surface water of this catchment is the Babaman river with Firooze, Bazkhane and Chenaran branches. From a geological point of view, the Bojnourd plain catchment is a part of the Kopedogh basin [13]. The oldest geological units, which have outcrop in the area belong to the Jurassic period (Fig. 1a). In General, the main part of the study area covered by Mesozoic units (Jurassic and Cretaceous). The Bojnourd aquifer is an unconfined aquifer that is surrounded by mountains. The maximum thickness of the alluvial aquifer varies from 80 to 90 m (in the NE and the center of the aquifer), and the minimum thickness is about 20 m in the northwest of the aquifer. A fairly thick (CA 180 m) marly clay sediments of Neogene age underneath the alluvial deposits and bounds the aquifer from the bottom [1].

In the shallow alluvial aquifer, the transmissivity (T) varies between 212 and 1188 m^2/d, depending on the spatial location, whereas the average specific yield (Sy) is about 0.05 [18]. Groundwater flow direction is, in general, from south and south west to the north and east (Fig. 1a). The depth to water table is increasing from south and the central to north of the aquifer and is varying between 4 m, north of the city, to 70 m, in the northern part of the aquifer. In general, the water table is shallow in most parts of the Bojnourd aquifer (especially in city domain) with a depth less than 15 m. The shallow water table in the central part of the aquifer is due to recharge induced by irrigation and by infiltrating runoff subsequent to rainfall events, as well as, recharging from the return flow of municipal wells which concentrated in city domain. Figure 2 shows the water table fluctuations in the study area during September 2005–2010 period, which correlates with the recorded precipitation. It can be seen from the figure that recharge from the precipitation events infiltrate into the aquifer system with a delay time about one month. The cause of this delay time is low hydraulic properties of upper layer including fine materials which cover the areas under the city.

CONCEPTUAL MODEL AND WATER BUDGET

The sources of water entering the system as well as the expected flow directions and exit points are the base of the conceptual model [2]. A water budget calculations are based on field data. Groundwater out/inflow was calculated using groundwater flow/equipotential maps and hydraulic parameters. The calculated net recharge is the sum of the recharge derived from irrigation and infiltrated runoff with considering an average of infiltration factor 45 and 5%, respectively [18].

(a)



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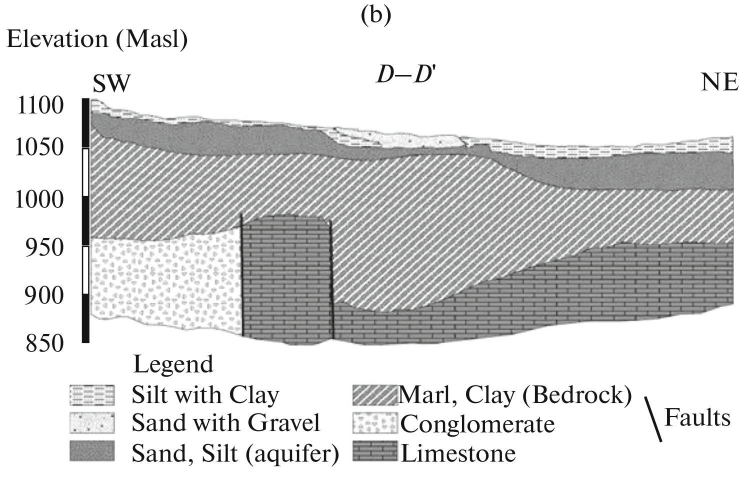

Fig. 1. Location and geological sketch of Bojnourd plain catchment, northeastern Iran (a); Geological cross-section, modified from [1] (b).

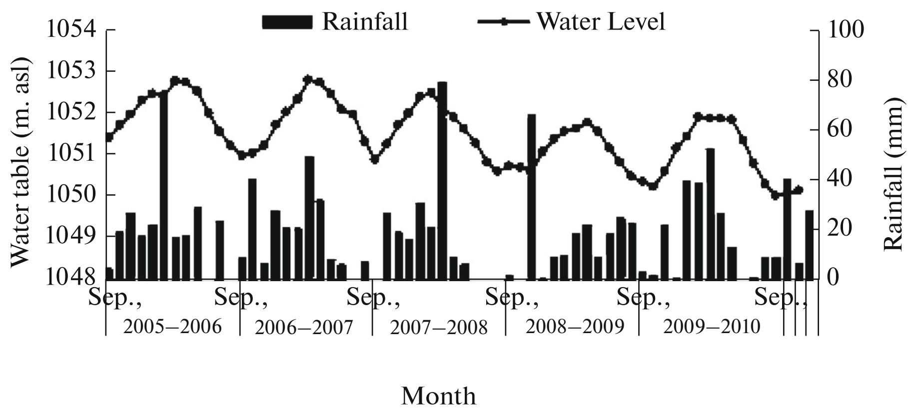

Fig. 2. Monthly water table fluctuations and rainfall amounts.

Differences in calculating total sources/sinks with the extracted volume of water from the aquifer, which was calculated based on groundwater unit hydrograph, show that the water budget calculations are fairly reliable. Then, the calculated water budget, based on field data, was compared with the computed water budget using the calibrated model (table).

After gathering required data, the aquifer conceptual model was prepared using Block Centerd Flow (BCF) package. Figure 3 summarizes the conceptual framework used to build the numerical model. Data from 12 observation points were imported into the model using the observation coverage ability in GMS interface. Other layers including sources and sinks, rivers, distributed recharge and hydraulic parameters were defined by the relevant packages.

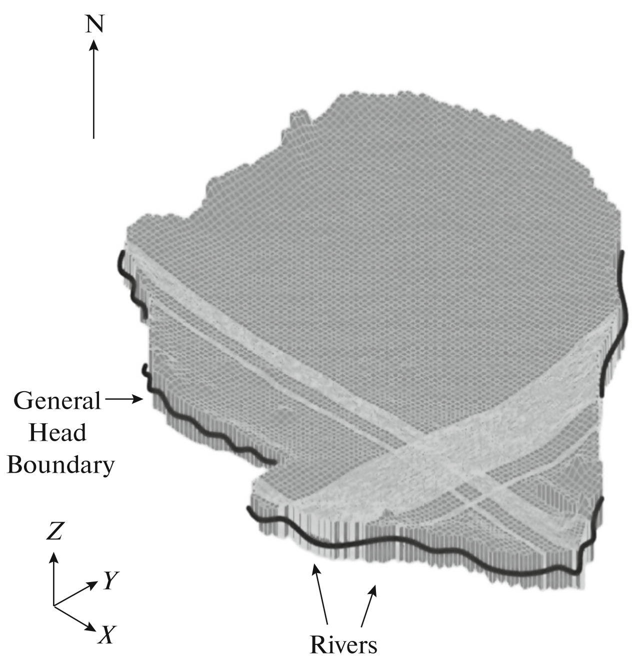

Fig. 3. Three dimensional model grid and boundary conditions type.

NUMERICAL MODEL SETTING

The numerical groundwater flow simulation of Bojnord aquifer was conducted using MODFLOW code [7] with GMS pre-post processor [6]. A study area of 65 km^2 and a single vertical layer was used in model conceptualization. The study area was discreted to 120 rows and 113 columns, with dimensions of 100×100 m by construction finite difference grid. The Preconditioned Conjugate-Gradient package (PCG2) was used to solve the finite difference equations in each step of a MODFLOW stress period. In order to be more accurate, smaller grid cells were considered in the rivers' locations (Fig. 3). Top and bottom layers' elevations of the shallow aquifer were derived from topographic maps, provided by North Khorasan Regional Water Company and Abkaveshargh Geophysical Company.

As mentioned earlier, the groundwater flow direction is from south and southwest to north and east (Fig. 1a), thus the southern and southwestern aquifer boundaries are groundwater inflow boundaries and the southeastern boundary is a groundwater outflow boundary. General head boundaries, which are normally allocated by specified head and conductance [2], were assigned to all aquifer boundaries in the model domain (Fig. 3). Rivers and boundaries (in/out flow) conductance to the model were estimated from field surveys. It is a preliminary value, and it must be changed during model calibration so that the model will be able to simulate recharge value of rivers and boundaries, which have been calculated using field data (table).

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

Water budget Parameters	Flow In (MCM/year)*	Flow Out (MCM/year)*	Flow In (m^3/year)	Flow Out (m^3/year)
Drains	0	0	0	0
General heads	6.21	–4.24	4705937.7	–3256891.35
Rivers	4.65	0	4677391.05	0
Wells	0	–20.56	0	–20568461.75
Recharge	13.8	0	14441871	0
Total Sources/Sinks	24.57	24.8	23825199.75	–23825353.1

* These values were calculated from the field data.

Steady State Calibration

After converting the conceptual model into grid cells, the numerical model was run for steady state conditions, and then the model was calibrated with observed head measured at 12 calibration targets distributed within the aquifer. The necessity to calibrate the model originates from the uncertainty in parameter values due to the number of assumptions and simplifications having been made in the conceptual and mathematical models [3]. Calibration was conducted through troublesome trial and error by varying aquifer hydraulic parameters, fluxes at the boundaries, recharge rates, river conductance, and comparing calculated head to those measured in observation points as well as comparing calculated fluxes across the boundary to those estimated using Darcy's law and field data. Best fit was obtained when the residuals between calculated and observed heads reduced to the defined tolerance of ±1 m. Model fit is commonly evaluated by visual comparison of simulated and measured heads or by comparing root mean square (RMS) errors of heads between simulations. Figures 4a–4b show the best fit between calculated and observed head and some statistical errors in the last execution of the model. The above mentioned results were achieved when the study area was divided into regions with different hydraulic conductivity (K) varied between 1 to 26 m/d.

Transient Calibration and Verification

Proper simulation needed to have the smaller cell size and time steps to display spatial and temporal changes in hydraulic head [17]. The time discretization in the constructed MODFLOW model started from Sep. 2007 to Sep. 2009, with a stress period of 3 months (90 days) and a time step of 1 month (30 days). In the transient conditions pertaining data, such as pumping rate, river stage, boundary head, recharge from rainfall and return flow were entered into the model proportional to the stress period lengths and used starting heads equal to the solution generated from the steady state model. The transient model calibration was carried out based on the groundwater hydrograph data from 12 piezometers (Fig. 5). This stage was performed by trial and error adjustments of hydraulic parameters such as Sy, K and river stage to the reach the best fit between observed and calculated heads. Finally, once the transient calibration was performed, a transient validation, simulation was performed for a 12 month transient period from Sep. 2012 to Sep. 2013. After optimization and confirming the accuracy of the aquifer hydraulic parameters, modeling water budget was obtained (table). As tabulated in table, differences between calculated and simulated water budget parameters are small, showing a fairly good simulation.

RESULTS AND DISCUSSION

Once the model was confirmed in the verification step, the future aquifer conditions can be predicted for different management scenarios. The first scenario is water supplying from Shirindare dam (about 20 MCM/year) to the city area with shallow groundwater level. The output of running this scenario makes it clear that what will happen in the future if the return flow of supplied water (40%) infiltrates into the aquifer. The other two scenarios, changing the exploitation plan from Bojnourd aquifer and assuming no recharges from surface and karstic reservoir, also

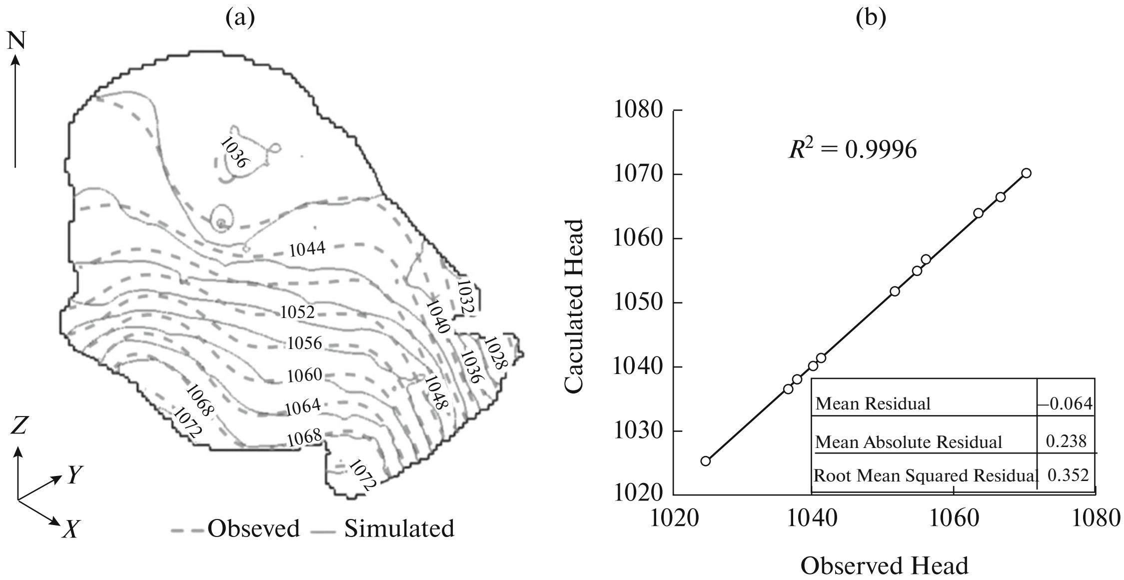

Fig. 4. Observed and simulated head contours (m) (a) and model statistical errors (b).

would eventuate in groundwater level rising. The response of the aquifer was examined for these three different scenarios.

Scenario 1—Supplying Water from Shirindare Dam

In this scenario, the model was executed for a period of one year and with five percent infiltration of maximum average annual rainfall (344 mm). In addition, it was assumed that 40% of supplied water from the dam (20 MCM/year or 54794.5 m^3/day), would be infiltrated into the aquifer within the city area (i.e., about 21917.8 m^3/day over 27 km^2). Figure 6a–6b show the simulated groundwater levels and the amount of increased groundwater levels in Bojnourd aquifer after supplying water from Shirindare dam. According to Fig. 6b, the groundwater level will rise by more than 3.5 m in some parts of the city, central part of the aquifer. Figure 7 shows the depth of groundwater level will be less than 2 m, in the city area, which may cause serious problems for the residents.

Scenario 2—Artificial Discharges

To deal with the groundwater level rising in the north east of the city, due to transferring water from Shirindare dam, it has been attempted to develop an exploitation plan in the critical areas of the aquifer, to reduce the water level and reach the equilibrium conditions. To achieve these purposes, a water withdrawal from 20 pumping wells for the whole year, except in winter, with a rate of 1278 m^3/day (approximately equal to the volume of return flow) was simulated around the critical parts. Figure 8a shows the depth of groundwater level in Bojnourd after implementing the exploitation plan in the aquifer. The result of this scenario shows that with proper management in aquifer exploitation during critical situations, not only will the groundwater level drop, but also the city can develop urban landscaping by constructing sports camps and cultural camping areas using the extra pumped water.

Scenario 3—Removing Recharges from Surface/Karstic Reservoir

Based on water budget results of model, the surface water resources such as rivers are recharging Bojnourd alluvial aquifer with an approximate annual magnitude of 4.67 MCM (table). On the other hand, the south and southwest karstic formations, as the main sources of groundwater inflow, are recharging the alluvial aquifer about 4.7 MCM, annually. The karstic formations are the main sources of groundwater inflow (Maharb. O. Company of Engineers, 2007). Therefore, increasing the withdrawal from these sources can reduce the groundwater level on the inflow boundaries. It was assumed that there was no aquifer recharge from the river and karstic formations. To have no recharges from karstic formations, 10 wells were adjusted on the aquifer inflow boundary. Figure 8b shows the depth of groundwater levels in Bojnourd aquifer after removing recharge from surface water and karstic resources. Based on the present conditions of the aquifer, it seems this scenario is relatively better than scenario 2. Since the karstic aquifers com-

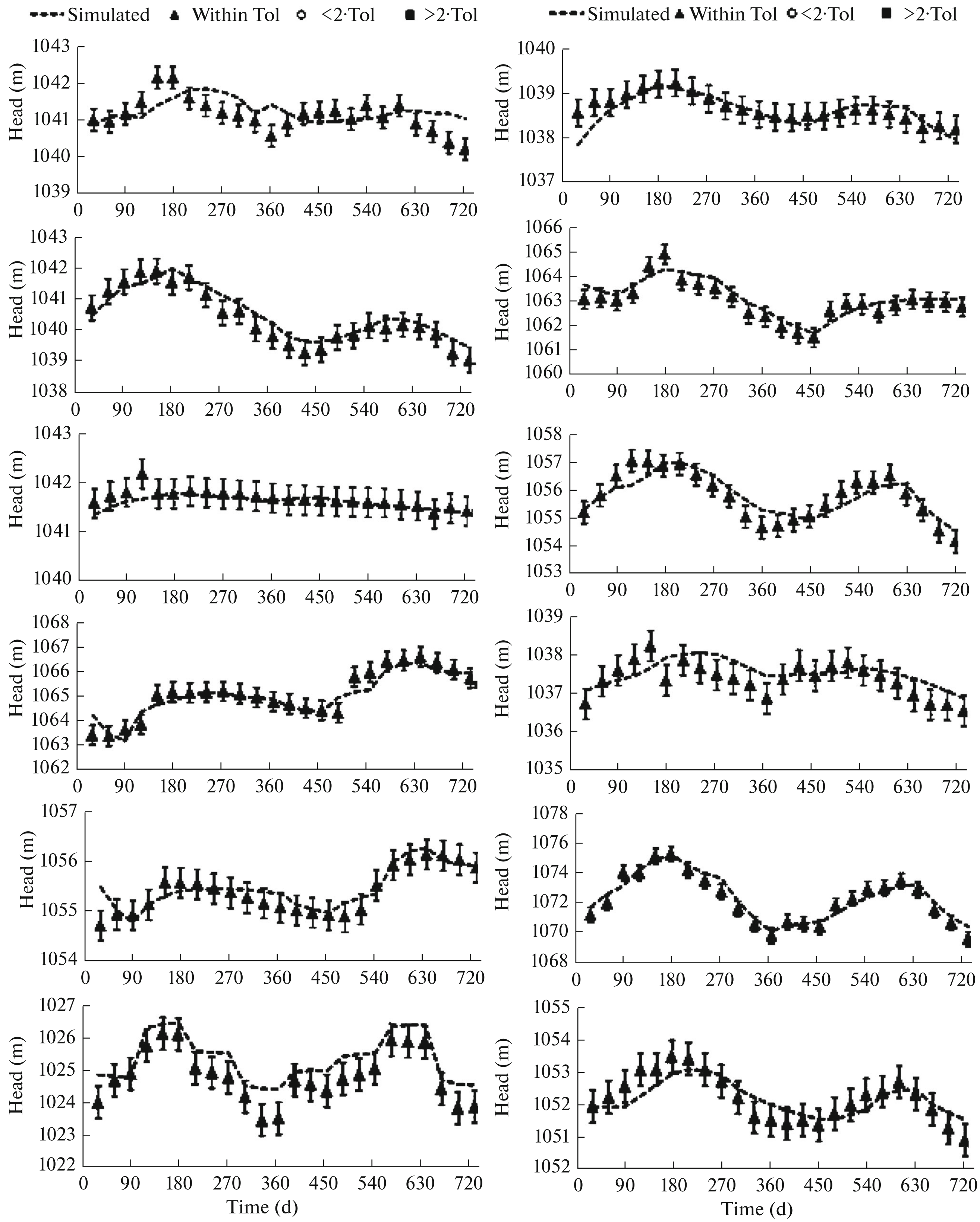

Fig. 5. Measured (▲) and simulated (– –) hydraulic heads.

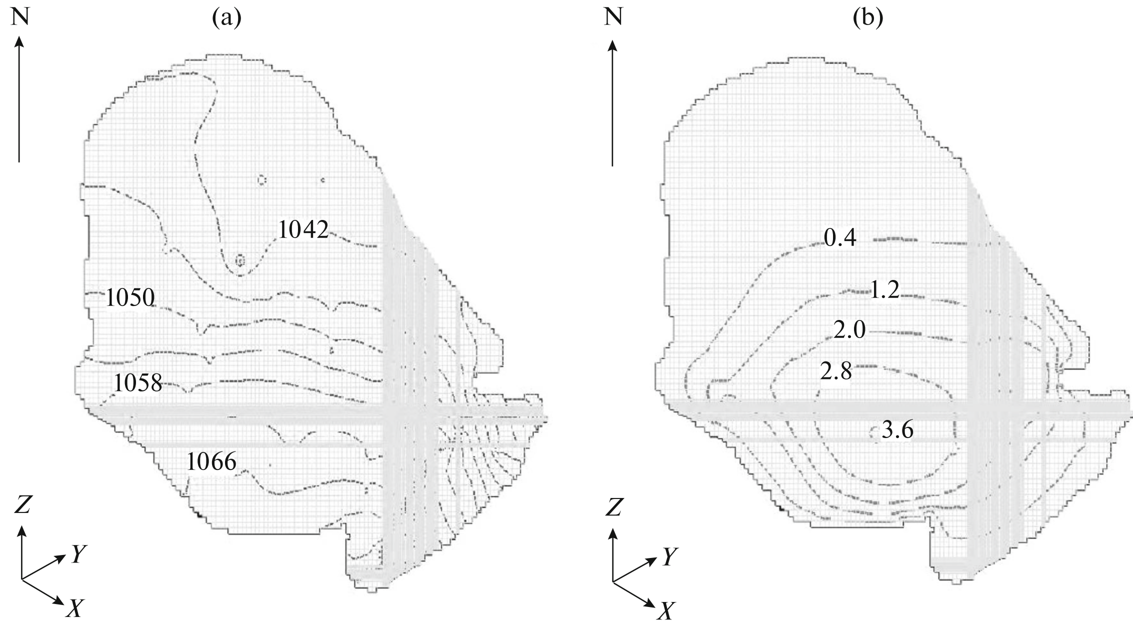

Fig. 6. Gruondwater level countors (a) and rising groundwater level countors (b).

pared to alluvial aquifers contain higher quality water, they can be exploited for inhabitants. Consequently, if proper plans such as building dam on the rivers and improving the exploitation plan from karstic resource are applied to surface water and karstic resources, a decrease in groundwater level in Bojnourd aquifer is expected.

CONCLUSIONS

In this study, groundwater flow system of the Bojnourd aquifer has been simulated using MODFLOW code in GMS interface. In addition, the future aquifer conditions have been predicted by applying three different management scenarios to the aquifer: (1) supplying water from Shrindare dam to Bojnourd, (2) changing the exploitation plan from Bojnourd aquifer, and (3) assuming no recharges from surface/karstic resources. Results reveal that by supplying water from Shrindare dam, the groundwater level will rise by more than 3.5 m in central parts of the aquifer. In order to manage the groundwater level rising, the exploitation plan from Bojnourd aquifer and also recharges from surface/karstic resources must be managed. In general, by building dams on the inflow surface waters (i.e. rivers); by proper alluvial aquifer exploitation plan; and by controlling karstic groundwater inflow, not only the groundwater level can be managed during critical situations, also the city of Bojnourd is able to develop the urban landscaping by

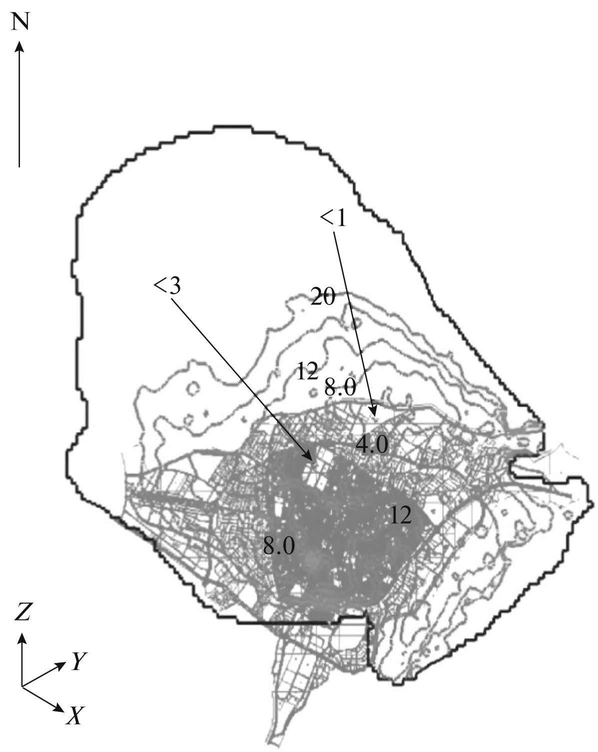

Fig. 7. Depth to groundwater level after applied 40% return flow to aquifer.

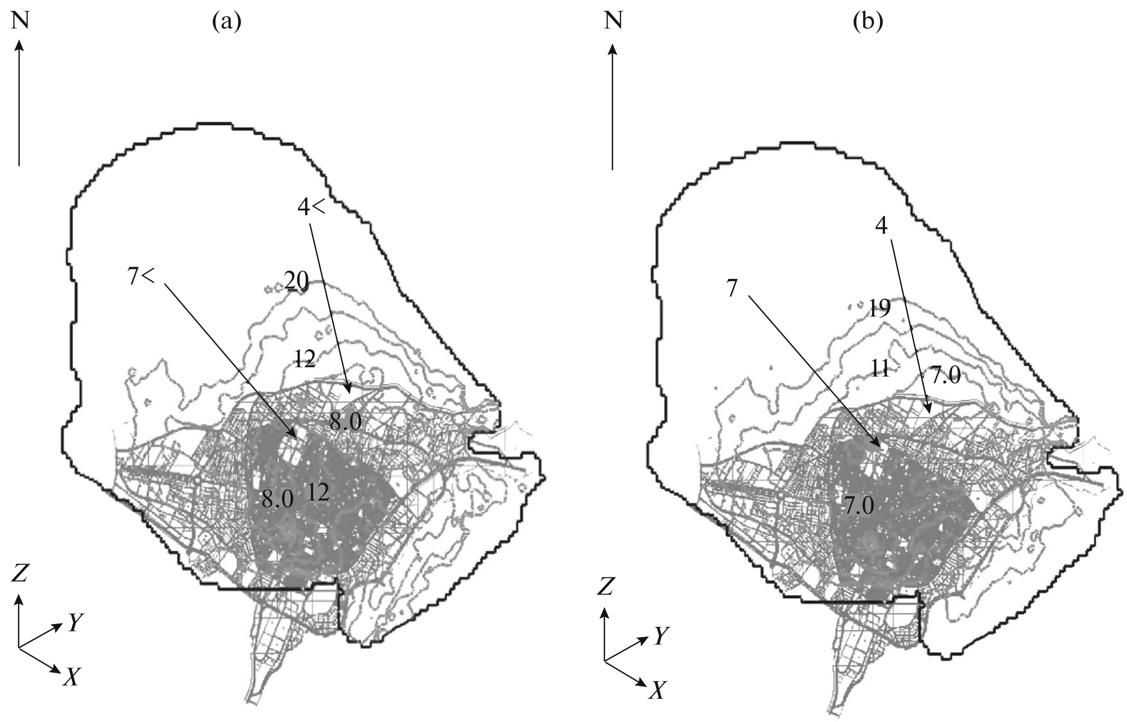

Fig. 8. Depth to groundwater level, after pumping artificial wells (a) and depth to groundwater level, after removing recharge from surface water and reducing karstic resources (b).

constructing sports camps and cultural camping area using the extracted water.

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