



Modeling the impacts of various managerial scenarios on groundwater level raising in a coastal aquifer

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Abstract

Groundwater abstraction management is one of the most fundamental steps towards the sustainable development of these resources. Recently, due to the excessive extraction of these important resources, the amount of groundwater storage has gradually depleted and the water scarcity crisis has worsened. In the groundwater depletion areas, managerial decisions can provide proper solutions to help change the rate of exploitation. Relying on mathematical models and through observation of the implications of such decisions, the best solution can be selected, and therefore, the sustainable use of groundwater may improve. One of these crisis-inflected aquifers is Shabestar's coastal aquifer located in the Urmia Saline Lake basin in northwestern Iran. In the current study, the Shabestar Plain aquifer was simulated by the MODFLOW mathematical model and 18 scenarios were defined for preventing water table reduction. This study tries to manage the groundwater resources and utilizations with different scenarios for sustainable use from the aquifer. These scenarios include changes in the extraction amount, close-off, or integrating several illegal abstract wells. For the first time, in the current study, the effectiveness of each of these solutions on the water table was investigated first separately and then collectively with other solutions. The results are indicative of a significant increase in the groundwater level in the scenario of extraction reduction from licensed agricultural wells due to a 30–40% decrease in licensed extraction from groundwater or through closing off all illegal wells along with a 20% decrease in extraction from licensed wells. The trend of reduction in the aquifer's water table can be slowed down, and the table can be maintained from the moment of application of these scenarios. Moreover, based on the modeling applied, closing off all illegal wells in the region or integrating them would lead to a 20 and 10% reduction in the extraction from the licensed wells in the area, respectively.

Keywords Managerial scenario · Numerical model · Groundwater modeling · Wells close-off

Introduction

Groundwater is one of the most important water resources in the world. Nowadays, due to technological and urban development, the need to use these resources is ever increasing. A reduction in rainfalls coupled with an increase in the exploitation of groundwater resources, especially over recent years, has led to the creation of sinkholes, land subsidence,

a sharp drop in groundwater levels, and the decline of its quality, as shown in various published research (Fogg and LaBolle 2006; Konikow and Kendy 2005; Maroufpoor et al. 2019; Rodell et al. 2009). Intense rivalry among freshwater consumers including agriculture, drink water, and industry, has always led to an increase in the limited resources of groundwater (Thevs et al. 2015). Meanwhile, the agriculture sector has increasingly outpaced other sectors (Godfray et al. 2010; Tilman et al. 2011). However, due to the need for higher production, the demand for allocation of water to the agriculture sector is ever-increasing (Cai and Rosegrant 2003), which is indicative of the water resources limitation challenge facing higher production in agriculture sector (Godfray et al. 2010). This challenge is getting worse with climate change and the increase in water demand by other sectors (Fader et al. 2016), as the UN has introduced water

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as the main limiting factor of agricultural development in the future (Water 2012).

In many arid and semiarid regions, farming is an important economic activity and the main source of employment as well as a source of income for farmers and villagers. Therefore, any changes in the quantity of water not only do affect agricultural produces but also impact economic development (Water 2016). In these regions, due to the lack of permanent surface water resources, extraction from groundwater is considered as a permanent source of development due to the development of deep wells drilling equipment and access to electrical energy, as in numerous reports (Foster and Loucks 2006; Konikow and Kendy 2005; Rodell et al. 2009; Scanlon et al. 2007; Shah et al. 2007; Siebert et al. 2010; Sophocleous 2010; Wang et al. 2008), weak management, and excessive extractions have been introduced as the reasons behind discharge of aquifer and an obstacle in the way of reliable development in the long term. Since groundwater has been historically used as a supplement to surface water, many researchers have stated that groundwater withdrawal may lead to the salinization of these resources in many coastal aquifers across the globe (Barlow and Reichard 2010; Bocanegra et al. 2010; Custodio 2010; Petelet-Giraud et al. 2016; Steyl and Dennis 2010; Werner et al. 2013).

An important challenge in groundwater management is which conditions can change the status of groundwater, so that the existence of a tool that can reflect the change in groundwater status by applying different conditions will be very valuable. Such predictions require that to quantify relationships among affected parameters, such as surface hydrology, climate drivers, agricultural water use, and groundwater responses (Sahoo et al. 2017). To achieve optimal management and reliable extractions, it is necessary to use a model to predict and simulate the aquifers' status based on their sustainability. With the recognition of the relationships ruling porous media and software and hardware capabilities, the use of different models for groundwater management and exploitation has been drastically expanded. Research on development and application of groundwater flows and transfer models has been significantly increased during recent decades (Chandio et al. 2012; Harou et al. 2010; Izbicki and Michel 2004; Lerner and Kumar 1991; Michael and Voss 2008; Simunek et al. 1998; Tyson and Weber 1964; Varni and Carrera 1998; Wang and Anderson 1995). Singh (2010) has also reported such models to be only a viable tool for managerial decisions, regarding their capabilities. Generally, what has been called a "model" for groundwater is the simulation of water flow in porous media (Mays and Todd 2005). These models can help predict the probable effects of an exclusive water management strategy. Therefore, the results of studies on the simulation of existing and proposed policies can set the basis for the identification of

proper water management plans in the future (Jhorar et al. 2009).

The numerical models of groundwater, which indicate the time and location of groundwater flow, are considered as the best methods to manage groundwaters and reach sustainable balance (Lubczynski 2006). The application of MODFLOW (Harbaugh 2005; Harbaugh et al. 2000; Harbaugh and McDonald 1996) as a popular numerical model for describing and predicting of groundwater systems has been the center of attention during the past decades in studies such as modeling groundwater in Southern New Mexico (Samani et al. (1995) and modeling of 3-D groundwater flow in Narborough Bog, England (Bradley (1996). In a study, Radmanesh et al. (2020) compared groundwater modeling methods and the results of their study showed that MODFLOW and Gene Expression Programming are more accurate in simulation among other simulation methods. In another study, Boufekane et al. (2019) modeled the Jijel Plain coastal aquifer in Algeria under different scenarios using a numerical model. Results of their research showed that maximum dropdown in groundwater level happened in the northwest of the study area, which suggested artificial recharge and modern irrigation for managing the development of groundwater utilization. Recio et al. (2005) prepared the 3-D model of the zone by using MODFLOW to study the hydrodynamic attributes of an aquifer for managing groundwater in La Mancha, Spain. Dewandel et al. (2017), in addition to providing a hydraulic conductivity map and identification of heterogeneity in this aquifer, provided a map for transmissivity of this region, which can be used as an initiation to modeling in an aquifer in New Caledonia. In all related literature, the present conditions of many aquifers in different places in the world have been modeled and sometimes managerial scenarios have been applied. In recent years, the Shabestar Plain aquifer has been in critical conditions and, due to the excess of groundwater abstractions leading to highly declining groundwater levels, the direction of groundwater flow has shifted to exploitation wells (Barzegar et al. 2019). In the current study, in addition to using managerial scenarios, extraction of the ruling curve has also been done to compare the results of applied scenarios in a critical coastal aquifer. The current study aimed to investigate the groundwater status in the Shabestar Plain aquifer and modeling based on the existing conditions in the best possible form. It aimed to investigate to what extent the changes in the groundwater levels can be affected with the application of the managerial scenario of reducing extractions and closing off and integrating illegal wells which are exploiting this aquifer. The problem of groundwater abstraction has not yet been studied by the ruling curves in this area, and the application of managerial scenarios in this way will help improve the status of groundwater. The obtained results

would be presented as managerial suggestions to increase the groundwater level or stabilize its changes.

Methods and materials

The Shabestar Plain is located in the western part of Eastern Azerbaijan Province as one of the 25 sub-basins of the Urmia Lake basin, which is located 60 km west of Tabriz City. The largest residential areas in this region are Shabestar, Sufian, Khameneh, and Shend Abad cities. The total area of this district is 1254.7 km², making up 2.42% of the total Urmia Lake basin. From this area, 638 km² is covered by plain and 616.7 km² by mountains. This district borders the Mishow Mountain to the north, the Tabriz Plain to the east, the Urmia Lake and its salt-clay flats to the south, and the Tasooj Plain to the west. Based on the borehole logging information, the Shabestar Plain aquifer is a water table aquifer with a total area of 484.6 km². The annual rainfall is about 310 mm in the study area, and the climate of this region is semi-arid and cold category, according to De Martonne and Emberger methods (Barzegar et al. 2019). In Fig. 1, the location of the Shabestar aquifer, as well as that of the Urmia Lake, has been illustrated. As the figure shows, the southern border of the aquifer is located in the vicinity of the northern part of Urmia Lake. However, in the last decades due to the decrease in the water level of the Urmia Lake, the Shabestar plain is bordered by salt marshes to the west and southwest, while nearly white salt and clay deposits constitute the southern border. The Shabestar plain to the north is characterized by the Barut and Kahar Formations, igneous rocks, marly and massive limestones, Conglomerate deposits, Quaternary terraces, and flysch (Mehr et al. 2019).

Status of Shabestar Plain coastal aquifer

Changes in water levels in the Urmia Lake and Shabestar aquifer from 1986 to 2017 are shown in Fig. 2. Investigation of the status of water level indicates that during recent years, the Urmia Lake water level has dropped 7 m and the aquifer water levels have also declined by an average of 10 m. As is seen, the drop in both reservoirs of Urmia Lake and Shabestar Plain aquifer has been similar in terms of the declining trend. Indeed, the current study is not aimed at investigating whether or not there is a relationship between these two resources, rather it explains how one clear reason behind this similarity is the increase in water consumption by the agriculture sector. The increasing agricultural water consumption has led to the extensive construction of licensed and illegal wells in the Shabestar Plain aquifer and extraction of water from the Urmia Lake basin's rivers for irrigation cutting or adversely reducing the ecological water right of the lake.

Figure 3 shows the distribution map of licensed and illegal wells in the study area. Almost 825 licensed and illegal wells withdraw 90 million cubic meters of water from this aquifer. Depletion of groundwater due to excessive extraction from the aquifer has led to gradual land subsidence in the region, according to Fig. 4. Moreover, reports and studies have been provided regarding subsidence in this area (Karimzadeh and Matsuoka 2020; Nadiri et al. 2018). As is shown in Fig. 2, the decline in water levels has reached 2.21 m from 2008 to 2015. The decline in groundwater levels during the past 7 years (2008–2015) caused land subsidence in this region, which has exacted damage to the facilities and some buildings in the area (Figs. 4 and 5).

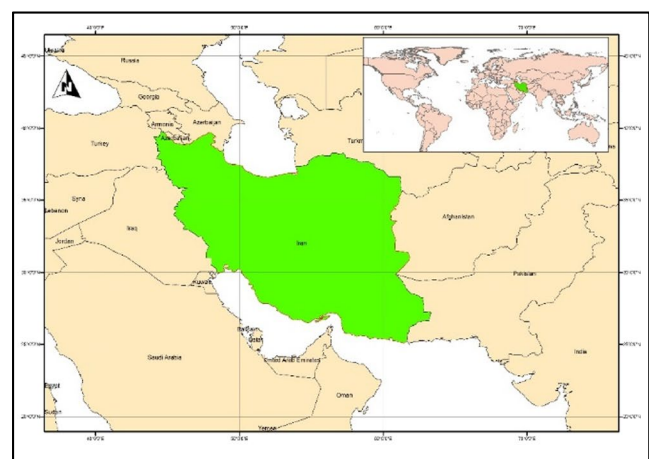
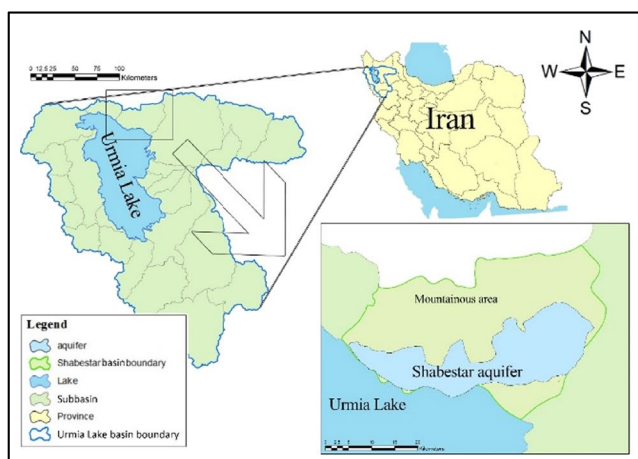


Fig. 1 Location of Shabestar Plain coastal aquifer

Fig. 2 Trend of Urmia Lake and Shabestar aquifer water levels during recent 31 years

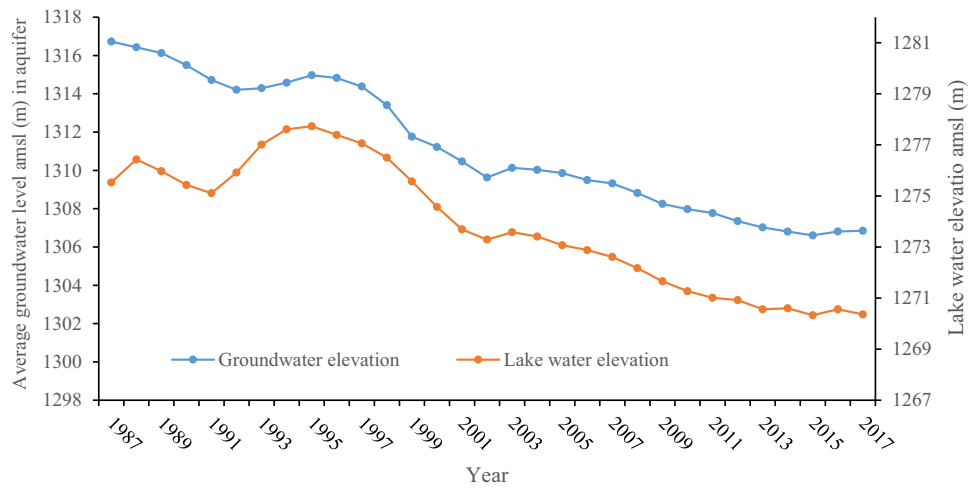
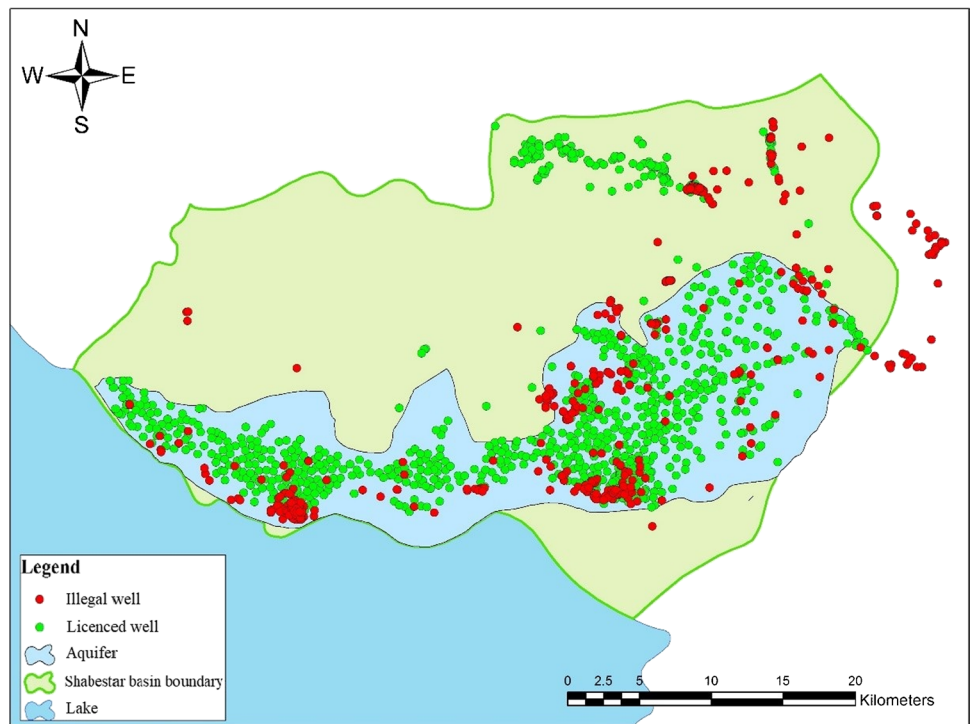


Fig. 3 Distribution map of licensed and illegal wells in Shabestar Plain aquifer



Model development and preparation of conceptual model

Groundwater models are mathematical tools for analyzing and predicting the aquifer behavior on a regional and local scale in different environmental conditions. These tools help us to see the result of applying scenarios to aquifers

by solving the following groundwater flow equation in transient modeling:

$$\frac{\partial}{\partial x} \left(K_x h \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y h \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z h \frac{\partial h}{\partial z} \right) + W = S_y \frac{\partial h}{\partial t} \tag{1}$$

where K_x , K_y , and K_z are components of the hydraulic conductivity tensor, W is the volumetric flux belonging to

Fig. 4 Gradual land subsidence in the Shabestar Plain due to groundwater withdrawal

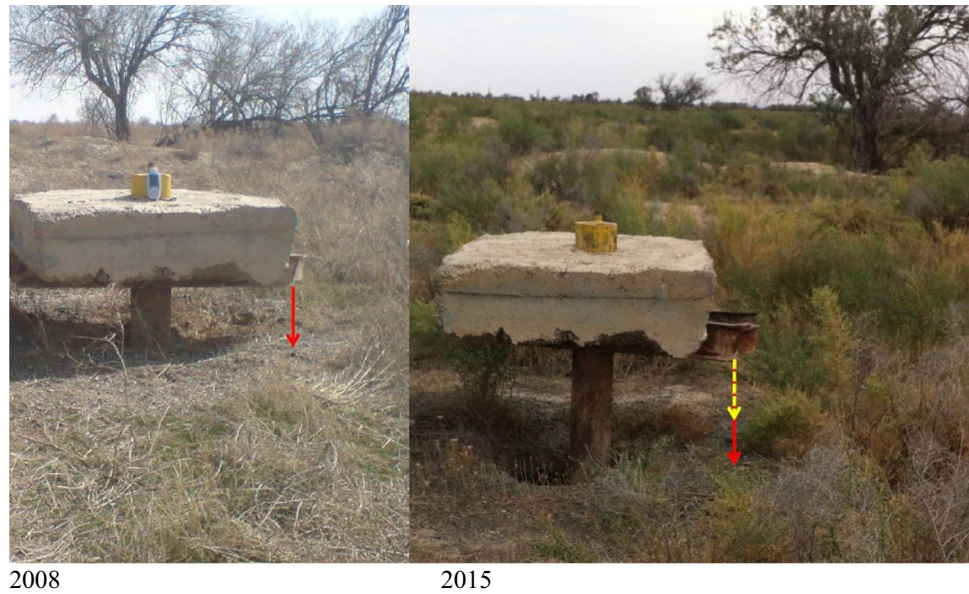


Fig. 5 Sinkholes and damaged buildings due to land subsidence (September 2015)



sources or sinks of water, S_y is the specific yield, and h is the hydraulic head.

Reliable aquifer conceptualization can be achieved by hydrological analysis and trial and error. Numerical models can be a good tool to understand the complex process of groundwater (Surinaidu et al. 2014). MODFLOW (McDonald and Harbaugh 1988) is a widely used and well-known modular 3-dimensional block-centered finite difference code used in the simulation of aquifers. MODFLOW-2005 is a version of this code that has been used in this research.

Pumping tests are typically used to obtain aquifer hydrodynamic parameters (Chang et al. 2021). But the lack of pumping test data from all over the aquifer may create a lack of information in the groundwater modeling. Obviously, if there was more information and data series on the aquifer,

the prepared model would be more precise. In this regard, the Shabestar Plain is also no exception, and the lack of data, and especially non-validated data in terms of modeling, has made the process of model preparation and implementation difficult. In the present project, for the Shabestar Plain aquifer, according to previous studies (Aghlmand and Abbasi 2019; Surinaidu et al. 2014; Taviani 2011) and as most wells have been reported at a minimum distance of 300 m from each other, discretization of the model has been done based on a 250-by-250-m grid.

Since the type of the Shabestar aquifer is unconfined, the top surface in modeling would be the ground's surface. The ground surface height was extracted from the ASTER sensing images, and the aquifer bottom bedrock level has been extracted from geoelectrical sections to be used along

with the log of the explorative and piezometric wells for modeling.

In order to study the aquifer, the piezometric data from 2012 to 2015 has been used. The piezometer positions and the water table contour map for September 2012 have been shown in Fig. 6. Twenty-eight piezometric wells which had good distribution in the aquifer area and had sufficient and reliable statistical data were chosen. The water tables of these piezometers were entered into the model as monthly data.

In order to determine the hydraulic conductivity of the aquifer, all the existing information from the region including the results of pumping tests and geological logs of the piezometric wells have been used. Lack of data is one of the problems of this plain. But by using the available values of pumping tests and the information available in the drilling logs, albeit not large, based on reliable references, the obtained values of hydraulic conductivity have been revised by using the values reported in the reference (Todd and Mays 2005) to different points in the aquifer. The aquifer is zoned to include spatial changes in hydraulic conductivity,

geological thickness, and geological structure to have more flexibility in determining the related parameters. Table 1 shows the characteristics and parameters used in aquifer modeling.

Initial and boundary conditions

To get a specific answer for a particular conceptual problem, more data on the physical condition of the problem is necessary. This additional data can be provided by initial and boundary conditions. Typically, boundary conditions determine sources and sinks in groundwater (Rushton and Redshaw 1979). To solve non-steady-state type problems, initial and boundary conditions are required, while for getting a solution for steady-state types of problems, only boundary conditions are needed (Omar et al. 2020). In the groundwater flow modeling, boundary conditions signify the positions, where water flows into or out of the model area due to any external factors. Inlet or outlet boundaries of aquifer, river, evapotranspiration, recharge, wells, and lakes are some common boundary conditions. Also, the initial conditions of the

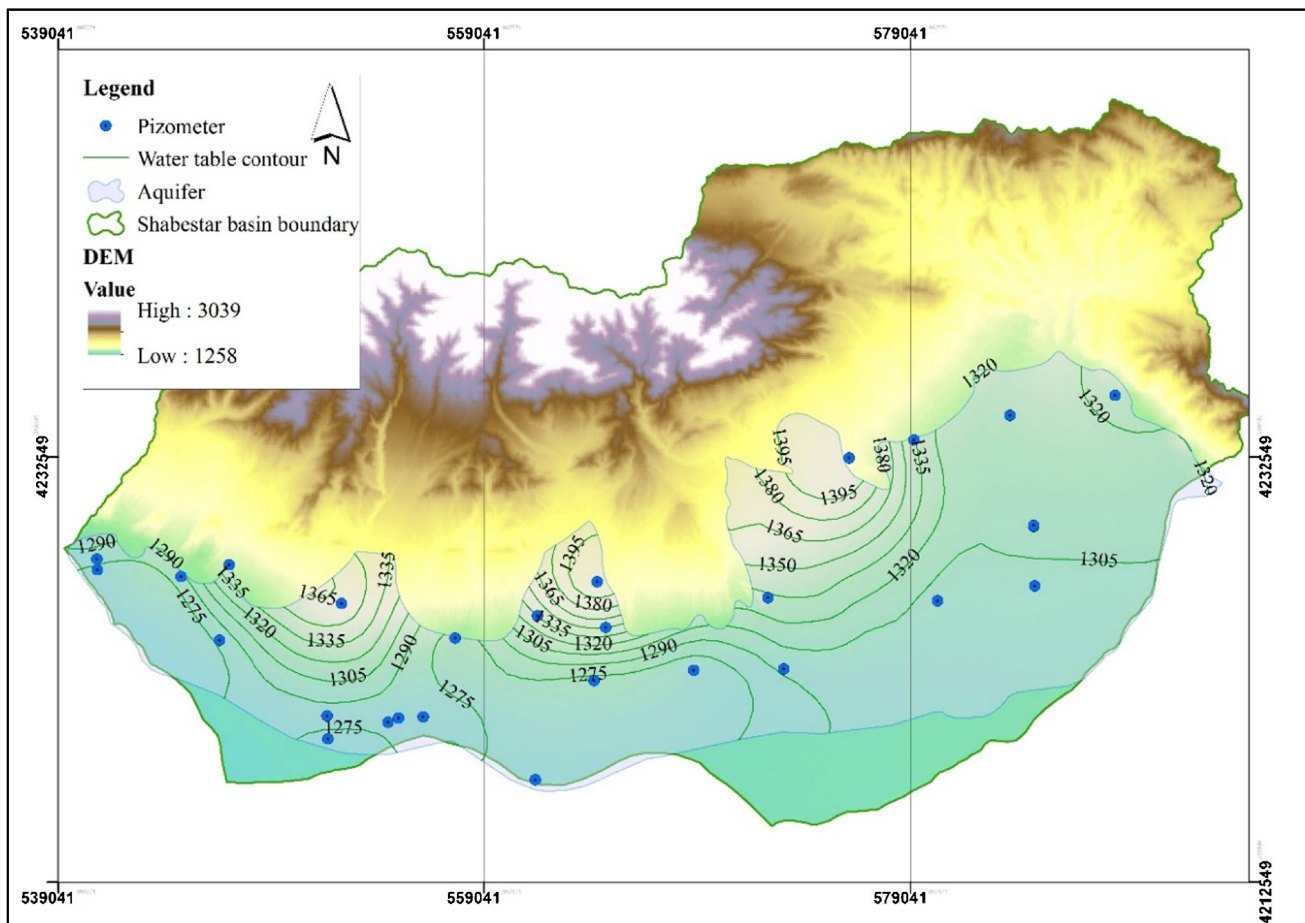
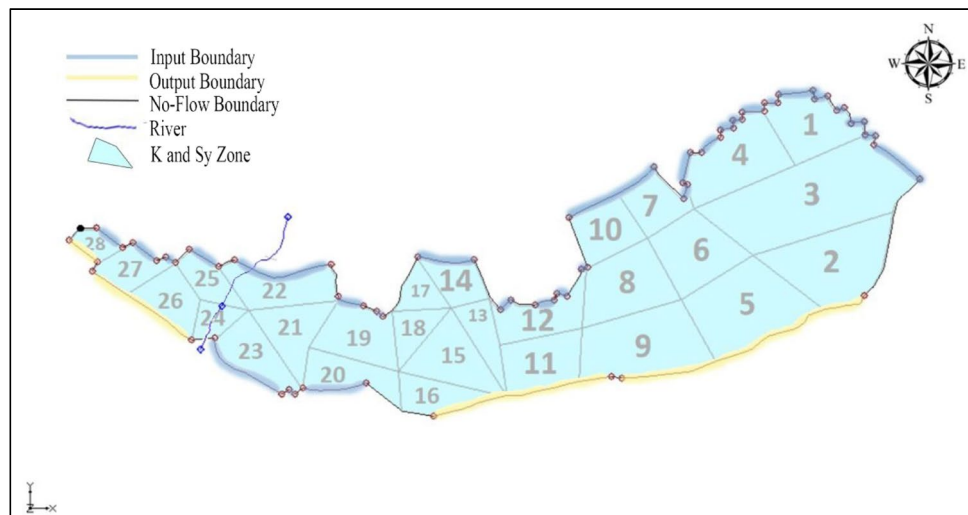


Fig. 6 Water table contour map in October 2012 (coordinate system: WGS1984 UTM zone 38 N)

Table 1 Characteristics and parameters of the aquifer

Parameter	Counts	Value		
		Min	Max	Mean
Elevation	-	1280 m	1443 m	1282 m
Piezometers (GW elevation in October 2012)	28	1273 m	1398 m	1307 m
Pumping tests (transmissivity)	11	45 m ² /day	2974.49 m ² /day	450 m ² /day
Borehole logs	41	-	-	-
Hydraulic conductivity (point)	41	0.5 m/day	30 m/day	5 m/day
Thickness	-	30 m	300 m	90 m
Storage	41	5.5%	16%	8%
Time steps (month)	36	October 2012	September 2015	-

Fig. 7 Boundary conditions and zoning of Shabestar Plain aquifer



model in the non-steady state are extracted based on the results of steady-state modeling.

Boundary conditions in the modeling of the aquifer have been shown in Fig. 7. Input and output boundaries are determined based on the groundwater level contour map and flow directions. Also, in 2012, about 825 wells including licensed and illegal agricultural, industrial, and drinking water wells had been located in the aquifer with a total annual discharge of about 90 MCM (million cubic meters).

Regarding the different types of boundaries, according to similar studies (Parhizkar et al. 2015), the boundaries along equipotential lines have been considered as boundaries with a general head, and the other boundary parts have been considered as no-flow boundaries (Todd and Mays 2005). The parameter needed for modeling is the amount of aquifer recharge from rainfalls. According to Kotchoni et al. (2019) studies, the recharge amount from the Shabestar Plain alluvial sediments is considered 7% of the average 10-year rainfall (2010–2020). Due to the seasonality of the Daryan Chai River, it has a small flow in dry seasons and it was inserted into the model as a line from north to south of the aquifer using the river package (RIV) in the model. This

river was entered with the starting and ending control points including information such as the riverbed level, water level in the river, and the riverbed transmissivity.

Calibration and application of scenario

For calibrating in the steady state, the changes applied based on the effective factors including the physical conditions of the aquifer as well as the discharge and recharge during this period.

After assuring the efficiency of the model in the flow simulation and proper estimation of the groundwater level in the calibration period, the model was able to simulate the status of aquifer with the application of different scenarios. With the application of any changes in the input data, its result during the calibrated period, which is called “prediction period” from now on, can be observed. The scenarios introduced in the current study have a managerial aspect and include changes in extraction rate from licensed and illegal wells as well as closing off and integrating them. The scenario application is in a way that the model is run first without any changes in the extraction from September 2012

to September 2013 monthly steps (12 steps) and then by applying the scenarios understudy for the next 24 steps (for 24 months) until September 2015 in order to study their efficacy.

Evaluation criteria

The reliability of the model in terms of groundwater head can be checked using scale-based (i.e., RMSE and MAE) and percentage error-based (i.e., NRMSE) indices (Anderson et al. (1992) Gallardo et al. (2005)). In this study four evaluation criteria, viz. determination coefficient (R^2), the RMSE, mean absolute error (MAE), and normalized root mean square error (NRMSE) were applied as follows:

$$\text{RMSE} = \sqrt{\frac{\sum (x_o - x_i)^2}{n}} \quad (2)$$

$$\text{MAE} = \frac{\sum |x_o - x_i|}{n} \quad (3)$$

$$\text{NRMSE} = \frac{\text{RMSE}}{(x_o)_{\max} - (x_o)_{\min}} \quad (4)$$

where x_o denotes the observational values, x_i denotes the calculated values, and n is the number of available data. The NRMSE value is acceptable for values less than 10% (Coelho et al. 2017; Gallardo et al. 2005; Guiger and Franz 1996).

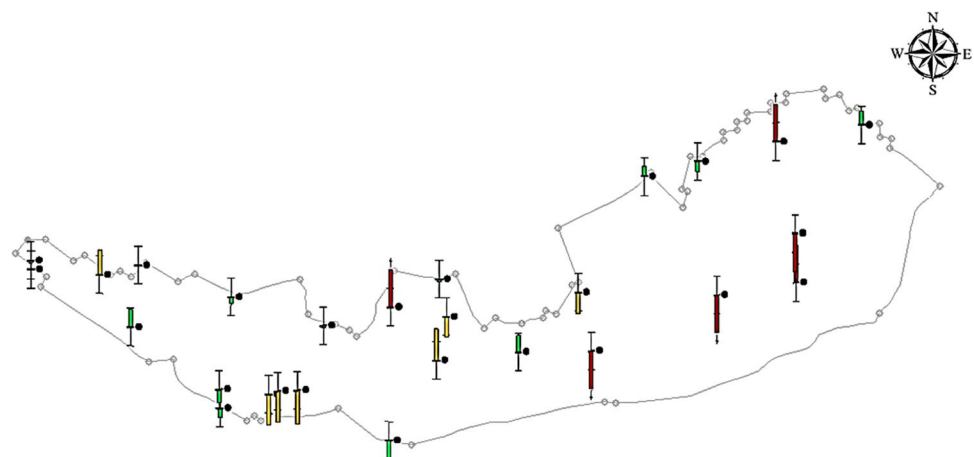
Results and discussion

In order to run the model in steady-state conditions, all the information needed including the recharges and discharges by water resources, the water level in the piezometers, and

recharge from the rainfall, riverbank, and hydraulic boundaries was all entered into the model for a constant 1-month period (September 2012) and, by considering the ground surface as the primary level of groundwater, the model was run under steady conditions, and the groundwater level was estimated by the model. Obviously, after the initial run, there were significant differences between the calculated and the observed water level. This difference is due to the uncertainty of the used data and the simplifications made, since the geological and hydrological structures of the aquifers have very high complexities that are so difficult to enter in the modeling, and in many cases, it is impossible. As is seen, despite all the precision and scrutiny adopted for the creation of the conceptual model and the screening based on the quality and acceptability of the input data, these differences emerged in the results that revealed the importance of calibration in the modeling stages (Fig. 8). Investigation of the observational data with the predicted results of water level in this stage shows the root mean square error (RMSE) at 3.24 m, which is a higher than standard error based on the rate of groundwater fluctuations. The acceptable values for RMSE in the simulation of groundwater level have been reported to be about 1 m (El Yaouti et al. 2008). Therefore, in order to increase the reliability of the study's results, the model needs to be calibrated with observational data. As is also seen in Fig. 8, from among 28 piezometers, more than half of them (the non-green candles) have an unacceptable calculation error and, in some of the piezometers (the red candles), this difference is too high. With the achievement of the desirable results of modeling in steady-state condition, modeling in the non-steady state would also be possible.

The calibration process is the most important part of the modeling whose time consumed depends on the number of parameters involved in the model and the precision of the data. In the steady-state condition, parameters such as hydraulic conductivity, recharge by rainfall, inlet and outlet boundaries, transmissivity rate on the inlet and outlet

Fig. 8 Status of existing piezometers error in pre-calibration run



boundaries, river conditions, recharge from the river, and correcting the errors driven by the bedrock interpolation were calibrated. After calibration, the model in the steady-state condition, hydraulic conductivity sensitivity analysis, has been driven by PEST (Doherty et al. 1994). PEST is a module for reducing the model error by changing the initial values and helps calibrate the model as accurately as possible by introducing more sensitive areas. Since this study is not a PEST-based calibration model, in this study, the model was manually calibrated and PEST was used only to analyze the sensitivity of different zones in hydraulic conductivity and storage coefficient. These zones are shown in Fig. 7. Based on the sensitivity of each zone, the field data recording precision can be increased, and more optimal results can be obtained. In this software package, the composite

scale sensitivity (CSS) parameter was used to calculate the sensitivity (Hill and Tiedeman 2006). CSS is a parameter whose value provided for each region in comparison with other regions indicates the sensitivity of the model to that region and its values. CSS values are provided in Fig. 9 to show the sensitivity analysis in the 27 zones. Based on the obtained results of sensitivity analysis, zone 13 with a CSS of 2.04 needs more precision and validation of information than other zones. Zone 21 is in the second rank. The rest of the zones had a CSS of about 0.5 and lower.

Through calibration in the steady-state and obtaining the optimal values of the calibrated parameters, the status of the existing piezometers in terms of the observational and calculative conditions is shown in Fig. 10. A comparison of the observational and calculative values of groundwater level to

Fig. 9 CSS values for sensitivity analysis of hydraulic conductivity in calibration stage

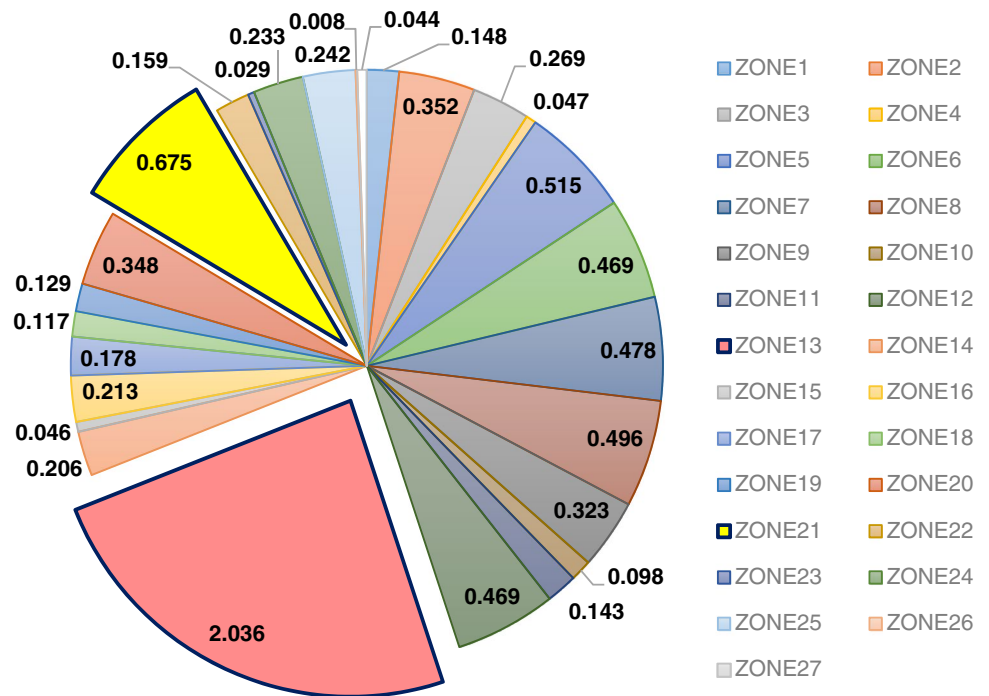


Fig. 10 Status of existing piezometer error post-calibration

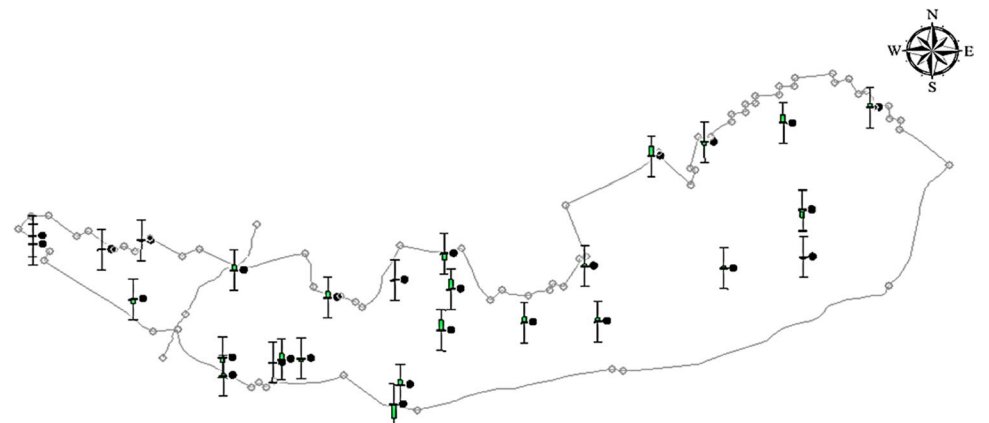
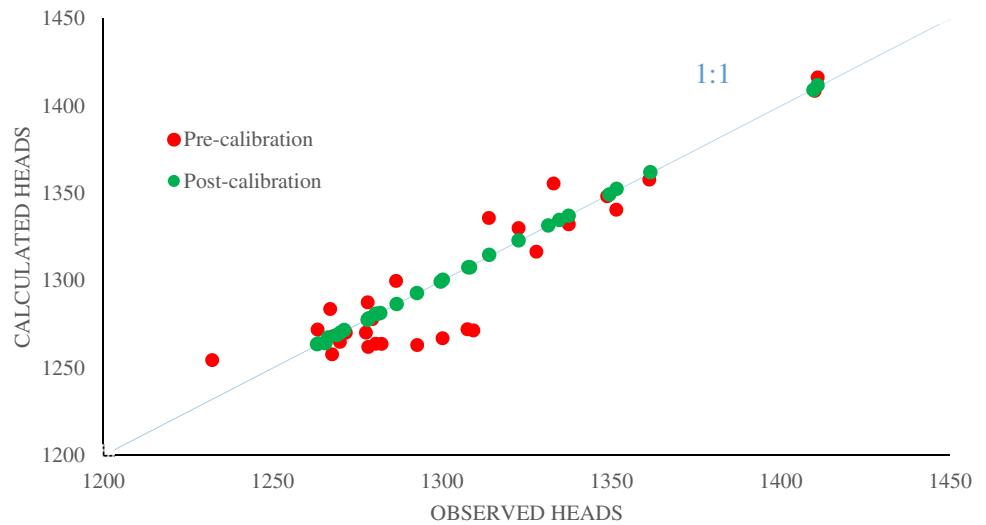


Fig. 11 Comparison between measured heads and calculated heads for pre- and post-calibration in steady-state



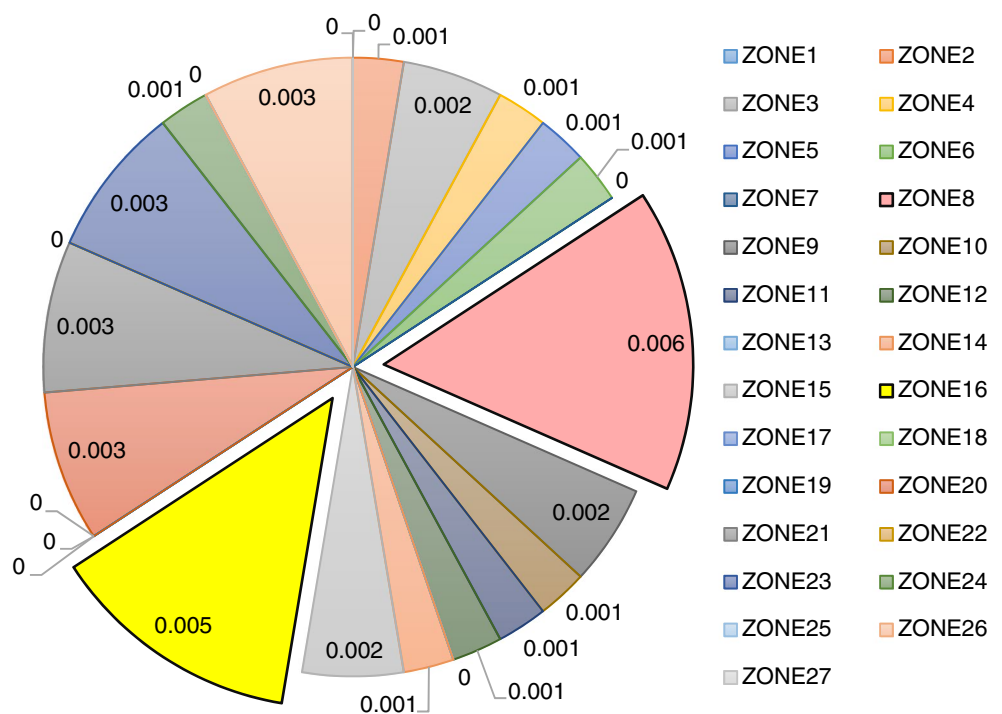
the bisector line in Fig. 11 shows the results of calibration in the steady-state conditions.

Regarding the acceptable results in the steady-state calibration section, the model was run in the non-steady-state condition in a primarily. After comparing the calculated results and observed values, the existing error still showed the necessity of calibration of the non-steady period due to the changes in the groundwater level in this stage. Due to the area's geological conditions being constant, after adding the specific yield parameter to the model, the parameters that were calibrated in the non-steady-state condition, including the aquifer inlet and outlet boundaries and their levels,

recharge by rainfall, and recharge from the river, were calculated for obtaining the acceptable water level in all months due to the changes in the passing discharge in all months of calibration and the unchanged monthly aquifer specific yield. The duration of calibration progress in the non-steady-state condition has a direct relationship with the quality of the calibration in the steady-state condition and also the number of time steps put in the non-steady-state condition. In the Shabestar aquifer model, this period was 3 years and the calibration was done in 36 steps.

After calibration in the non-steady-state condition, the specific yield values were entered into the PEST to analyze

Fig. 12 CSS values for specific yield sensitivity analysis in non-steady state



the sensitivity and the results of this analysis along with the CSS values related to the specific yield sensitivity analysis for the 27 zones have been shown in Fig. 12. The CSS coefficient values indicate that in zones 8 and 16, the sensitivity to the coefficient of storage has been more than other zones, and it is suggested that by using pumping tests, this parameter may be extracted for these zones.

A summary of information about the statistics of modeling is provided in Table 2 to show the model calibration precision in different steps for steady and non-steady-state conditions. The values of indices such as RMSE and NRMSE indicate that the model calibration precision is good as the

RMSE values are about 1 m. The results of the model calibration used in the Shabestar aquifer are in line with those of Karimi et al. (2019) for the Tehran aquifer and El Yaouti et al. (2008) for Bou-Areq in Morocco. The high correlation achieved between the observational and calculative groundwater levels is indicative of the sufficient precision of this model, and it can be used for the reliability of calculations and the prediction of the aquifer status after the application of the intended scenarios.

Figure 13 shows the difference between the observed groundwater values and calculated values. For this comparison, three different piezometers are randomly selected and

Table 2 The statistical summary of the comparison between the observational and calculative values of groundwater level

Period	Steady	Non-steady						
		Calibration						
Step	-	Total	Step 2	Step 6	Step 12	Step 18	Step 24	Step 36
RMSE (m)	0.59	0.95	0.44	0.63	0.79	0.60	1.09	1.28
MAE (m)	0.45	0.65	0.34	0.47	0.58	0.45	0.79	0.99
R²	0.9998	-	0.9999	0.9992	0.9996	0.9998	0.9993	0.9967
MR (m)	-0.07	-0.04	-0.06	-0.22	-0.08	-0.12	-0.03	0.17
NRMS (%)	0.3	-	0.2	0.4	0.5	0.4	0.7	0.8

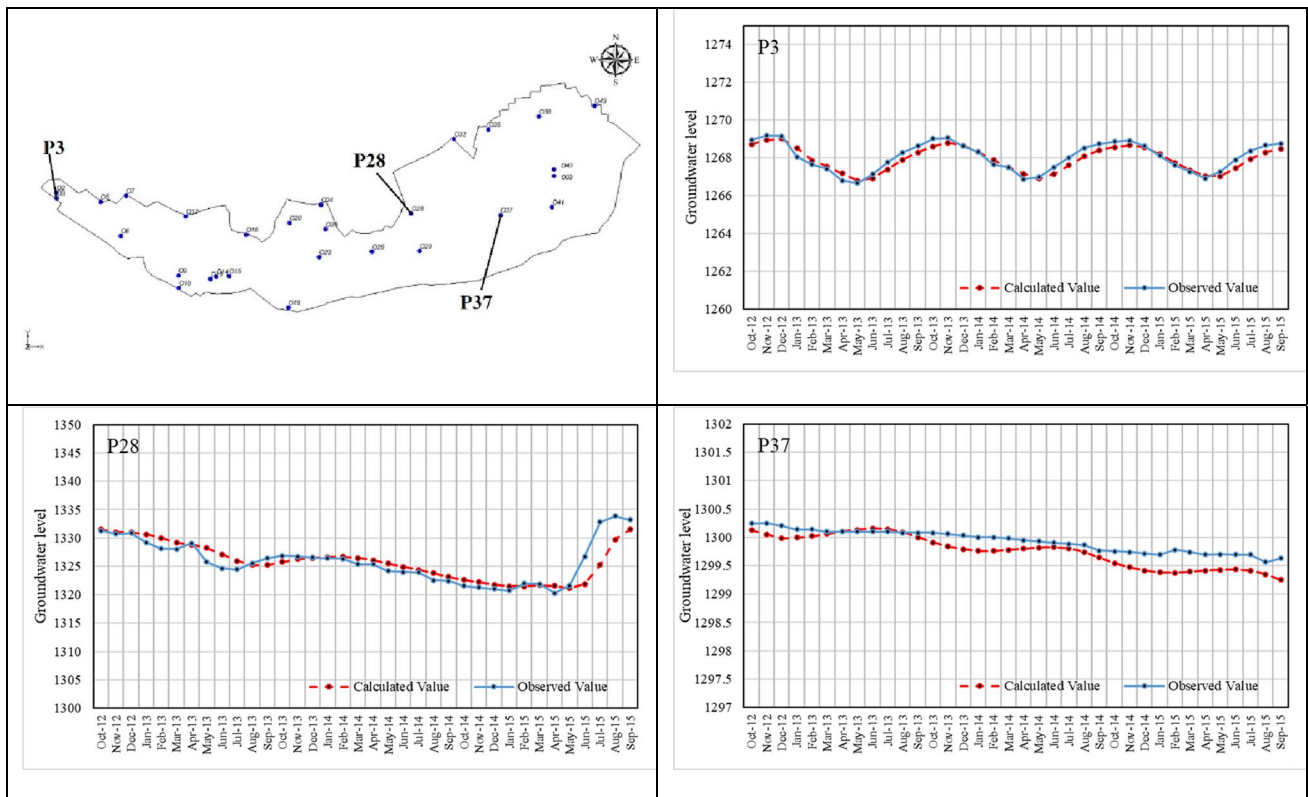


Fig. 13 Difference between observed and calculated head values in three selected piezometers includes piezometers 3, 28, and 37 at the end of model verification for 36 months

their time-series curves are plotted. The simulated hydrographs of the observation wells exhibited good agreement with the corresponding observed hydrographs.

Application of scenario

Simulation of the impact of illegal wells on the aquifer

Many climatic scenarios have been implemented on groundwater (Avcı et al. 2021; Rastegar and Paimozd 2020; Shrestha et al. 2020), but less has been discussed on management scenarios, including control and change in groundwater abstraction. Among the studies of other researchers, scenarios of change in abstraction rate have been presented not so widely. Some of these recent studies that have declared the control of abstraction rate as a factor in the sustainability of groundwater are Bayat et al. (2020) and Qin (2021) researches. However, the most accessible mode possible to achieve sustainable groundwater use can be controlled at abstraction. This scenario was applied from step 12 onwards. Drawing of the hydrograph of the general status of the Shabestar Plain aquifer after the application of this scenario is shown in Fig. 14. Investigation of the results in the figure showed that the increase in groundwater levels in the first and second years will be 20 and 30 cm, respectively. The role of closed-off illegal agricultural wells in the improvement of aquifer status is undeniable, and the status of this aquifer can be optimally improved by this scenario. The investigation of the status of illegal wells in the area shows

that these wells are mainly traditionally, and due to the problems the exploiters face in supplying the pump's power, they are not able to abstract high volumes, according to Fig. 15. However, due to their high number making up one-third of the region's wells, they play an important role in governing the region's water, since if the illegal wells are not closed off, any kind of application of reductive policies for water extraction from licensed wells will bring about social tensions and resistance of from licensed well exploiters.

Decrease and increase in extraction of licensed wells

In order to observe the effects of management in the extraction rate of licensed agriculture wells in each scenario, after 12 steps of running the model with 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100% decrease in the extraction rate and 10, 20, and 30% increase in the extraction rate, and running the other 24 steps, the hydrograph of this aquifer for 3 years with 35 time steps is drawn in Fig. 16. In this part again, the application of the scenario was initiated from step 12 onwards (from September 2013 to September 2015). According to Fig. 16, the Shabestar Plain groundwater level was in a severe declining trend without the application of the scenario and it is a vulnerable aquifer in this regard. Kadkhodaie et al. (2019) have also reported the aquifer to be quantitatively and qualitatively vulnerable. However, after the application of the scenario of reduction in licensed agricultural wells, the overall groundwater level of the aquifer showed significant changes and, in a 30–40% reduction in

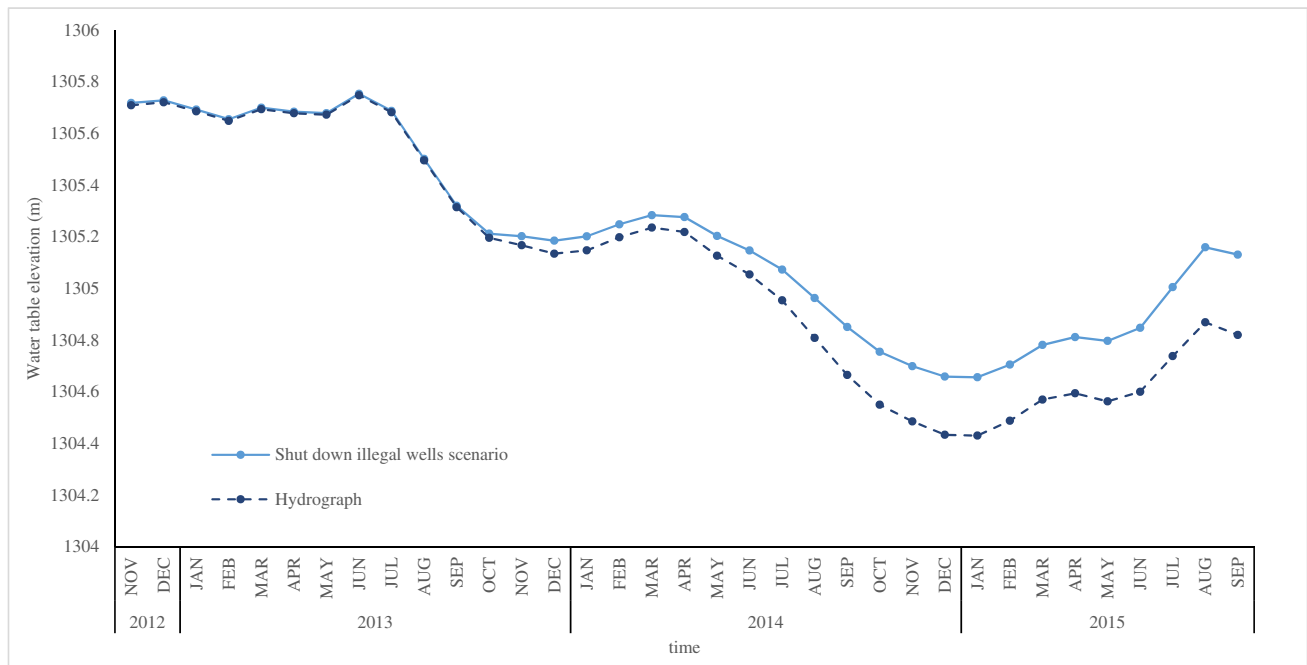


Fig. 14 Changes in Shabestar Plain groundwater level after the application of illegal wells shut down scenario

Fig. 15 Frequency of illegal wells discharge in Shabestar Plain

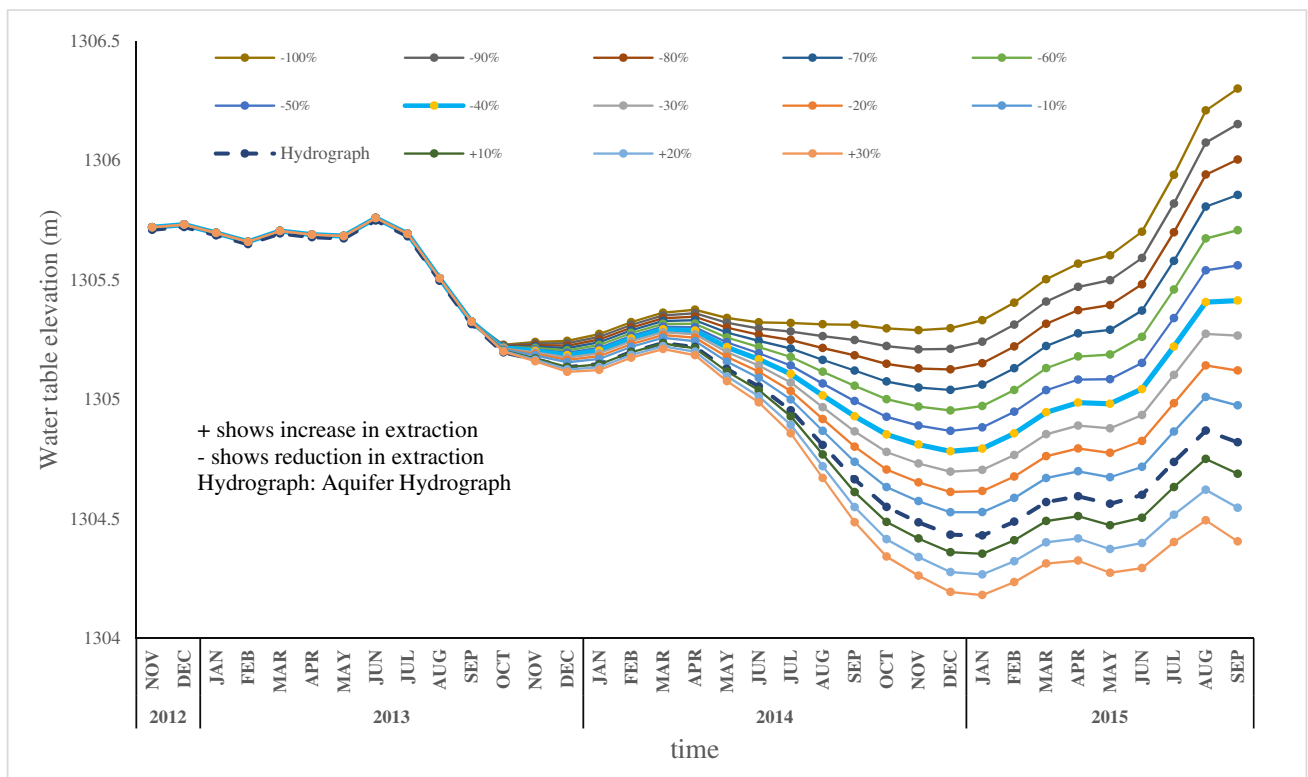
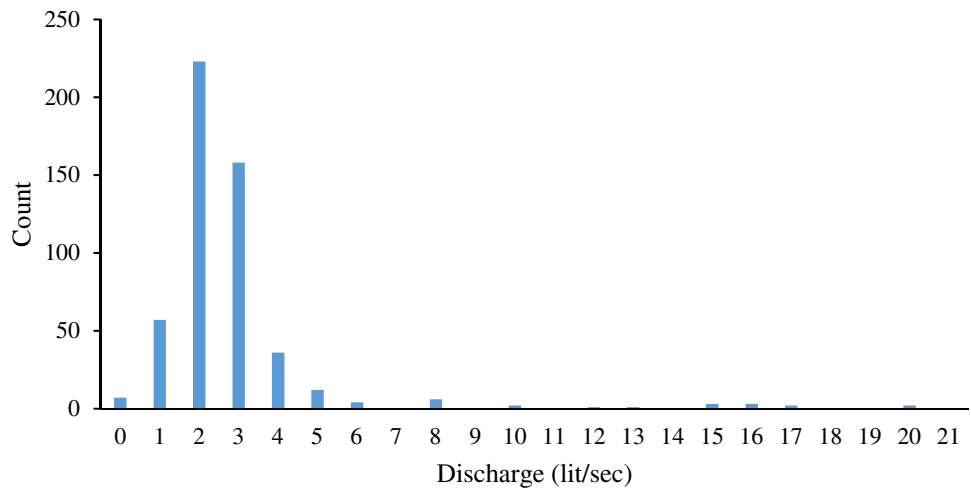


Fig. 16 Changes in the status of Shabestar aquifer groundwater levels after the application of extraction reduction scenario

extraction, it is seen that after 2 years, the conditions of aquifer groundwater recover to the conditions in September 2012, and the decline in groundwater levels is eliminated. This amount of reduction can be achieved by modifying the irrigation method of farmers and increasing the efficiency of the irrigation system. Such a reduction has also been suggested by researchers with studies in this area (Sarindizaj and Zarghami 2019; Sima et al. 2021). The different scenarios of reduction in extraction (from 10 to 100% which is

closed off) are a factor in the reduction of the declining trend and, in some cases, the elimination of this trend and even the rising trend of groundwater level. The obtained results have a good correlation with the results of a study done on the water management of the Mansurieh aquifer in Iraq, which is environmentally very similar to the Shabestar aquifer (Jalut et al. 2018). Investigation of the scenarios of increase in extraction, as expected, is clearly indicative of the intensity of the declining trend and inability of the aquifer in creating

a balance. This is despite the fact that the lowest reduction in extraction can have very important effects on the improvement of groundwater levels.

Integration of the illegal wells

Integration of illegal wells is considered as a mandatory solution for the reduction of social tensions. In a layer that was introduced to the model as the illegal agricultural wells, after 11 steps (which along with the non-steady period becomes 12 steps equal to 1 year), all the illegal wells were inactivated and replacements were considered for them. The illegal wells were eliminated from the calculation cycle in the next 24 steps, after calculating the area of irrigation by these wells which were obtained through cells including these wells, and then replacement wells providing irrigation hydromodule and necessary discharge were allocated for the mentioned area. In order to observe these changes in the overall level of the Shabestar aquifer water table, the aquifer's hydrograph in the two states of extraction without integration and extraction with integration is drawn in Fig. 17.

As is seen in this figure, the integration of illegal wells does not have a significant effect on the aquifer status; however, regarding the farmer's need for extracting these wells and the positive effect (though tiny) of this act on the improvement of groundwater status, this scenario can be prioritized. On the other hand, with the provision of the water

right of licensed wells to the illegal exploiters, the complete integration of illegal wells can be realized.

Combination of decrease in extraction from licensed wells and shutdown of illegal wells

This scenario was designed with the aim of achieving a 40% reduction in agricultural water consumption with the application of the lowest reduction in the extraction from licensed wells. According to the sustainable development index, consumption of 40% of the renewable water resources is the maximum allowable limit to avoid critical conditions. The overall extraction from licensed and illegal wells is about 90 MCM, and the potential renewable water in this region is 86 MCM, so 104% (4% higher than the renewable water level) is consumed by the agriculture sector. The objective of this combinational scenario was to investigate the possibility of achieving secure conditions with the lowest application of reduction in extraction from licensed wells. Therefore, the results of the two combined scenarios include a 20% reduction in the extraction from licensed wells and shutting down all the illegal wells beside a 40% decrease in the extraction from licensed wells along with shutting down the illegal wells, which is shown in Fig. 18. The consideration of the figure showed that after the application of the combinational scenario of a 20% reduction in the extraction of licensed wells and shutdown of all the illegal wells, after 2 years, the water level increased by 60 cm, and with the combinational

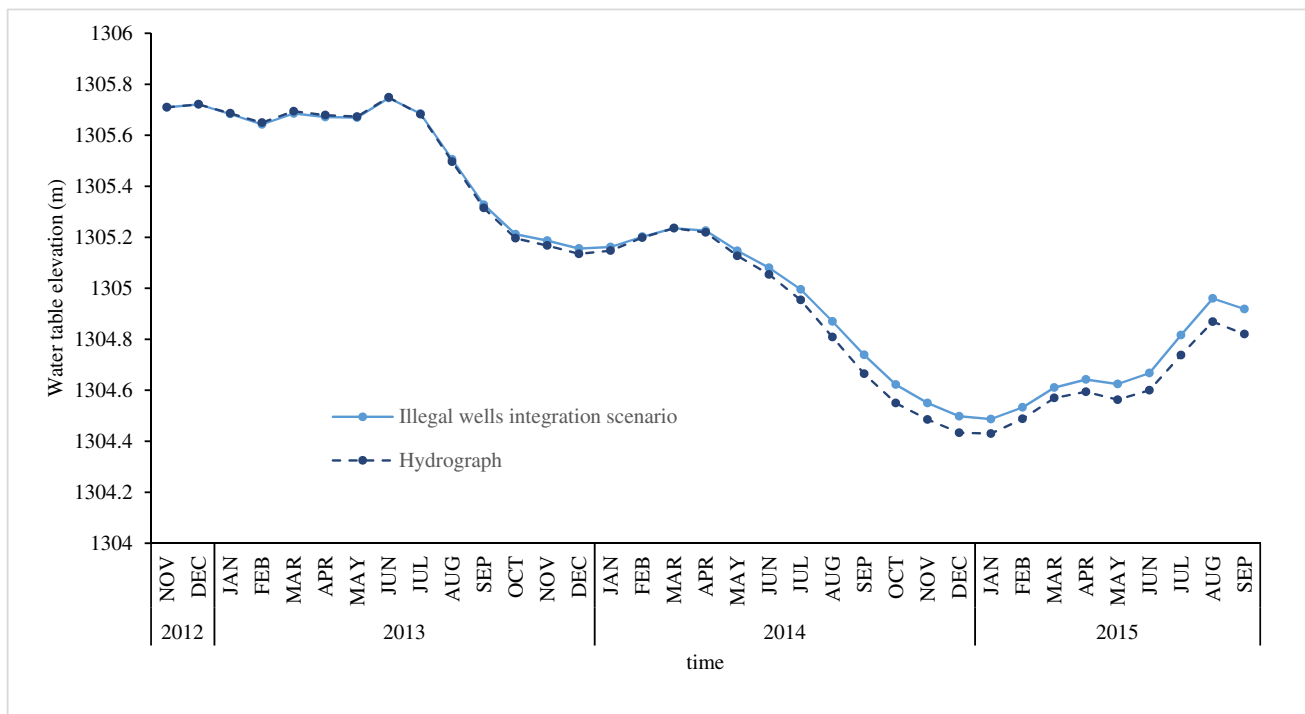


Fig. 17 Changes in the level of the Shabestar Plain groundwater after the application of the scenario of illegal wells integration

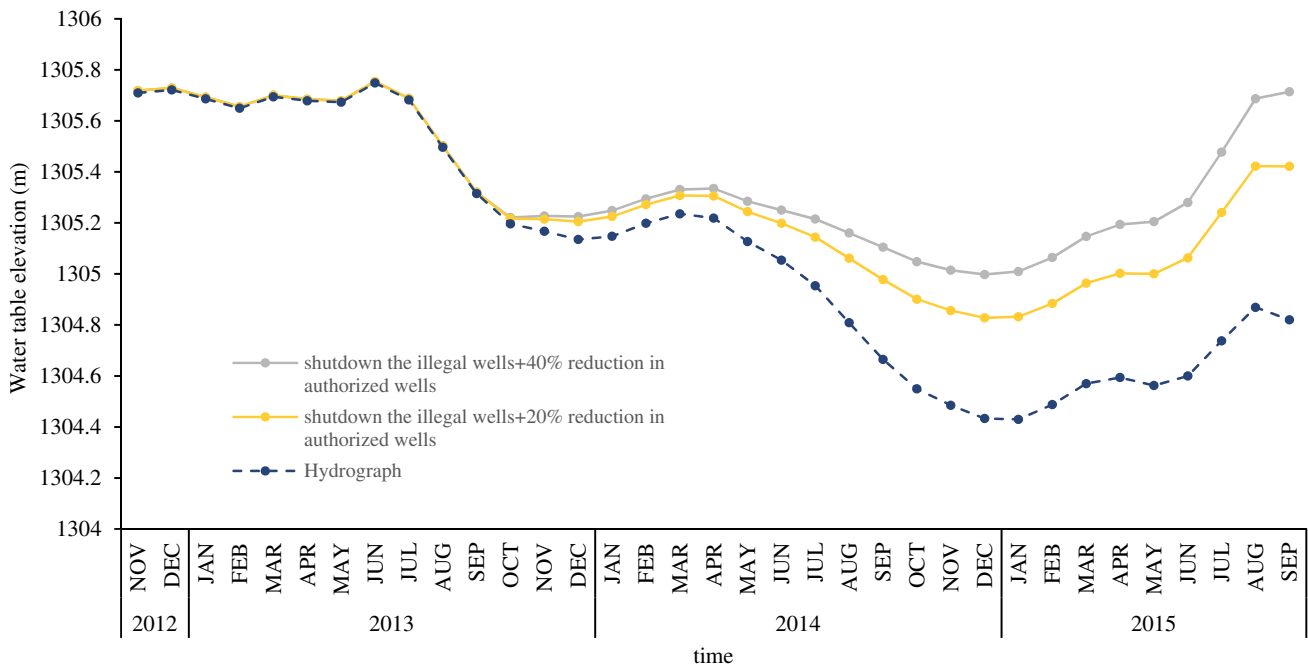


Fig. 18 Combinational scenario of reduction in extraction from licensed wells and shutdown of illegal wells

scenario of a 40% reduction in the extraction from licensed wells and shutdown of all illegal wells in the aquifer, the average water level increased by 90 cm.

Comparing scenarios

In this stage, the results and effects of all scenarios on the groundwater level variations in the Shabestar aquifer would be compared and are shown in Fig. 19. A comparison of the results showed that the effectiveness of the scenario of closing off the illegal wells in terms of the increase in aquifer water table is equal to the 20–30% reduction in the extraction from licensed wells. In case the illegal wells cannot be shut down due to social tensions, the extraction and level of the groundwater can be somehow managed through integration of the illegal wells and reduction in the percentage of extraction from licensed wells.

The next point is comparing the scenario of integration and application of illegal wells with the scenario of reduction in the extraction from licensed wells. According to Fig. 19, the effectiveness of the scenario of illegal wells, the integration is 10% lower than the reduction in the extraction from licensed wells. Based on the obtained results, it can be said that with the decrease in the extraction from licensed wells by 10%, more optimal results can be obtained rather than the integration of illegal wells. However, the integration policy can prevent social tensions.

The comparison between the combinational scenario of a 20% reduction in the extraction from licensed wells and

shutdown of illegal wells and the other scenarios showed that the results of this scenario are equal to a 40% reduction in the licensed wells consumption. However, with the combination of close-off of illegal wells and application of a 40% reduction in the extraction from the licensed wells, a result equal to a 60% reduction in the extraction from licensed wells would be obtained. Therefore, it can be said that with the application of the second combinational scenario, the aquifer’s consumption will reduce from 104 to 44%, and it would get closer to the value suggested by the United Nations Commission on Sustainable Development.

Conclusion

The Shabestar Plain aquifer, located in a cold semi-arid climate area, is in a poor condition in terms of recharge, which has led to a drop in the groundwater levels during recent years. In addition, the existence of numerous licensed and illegal wells in this region has increased the trend of this drop in groundwater levels, which is significant in some areas, due to the accumulation and high density of these wells. The presented modeling was performed based on basic information about this aquifer, and the principles of groundwater modeling. The results of the calibration period are indicative of the high precision of the model and its ability to apply the scenario. The results obtained from applying all scenarios showed that the groundwater level can be almost stabilized and this declining trend could

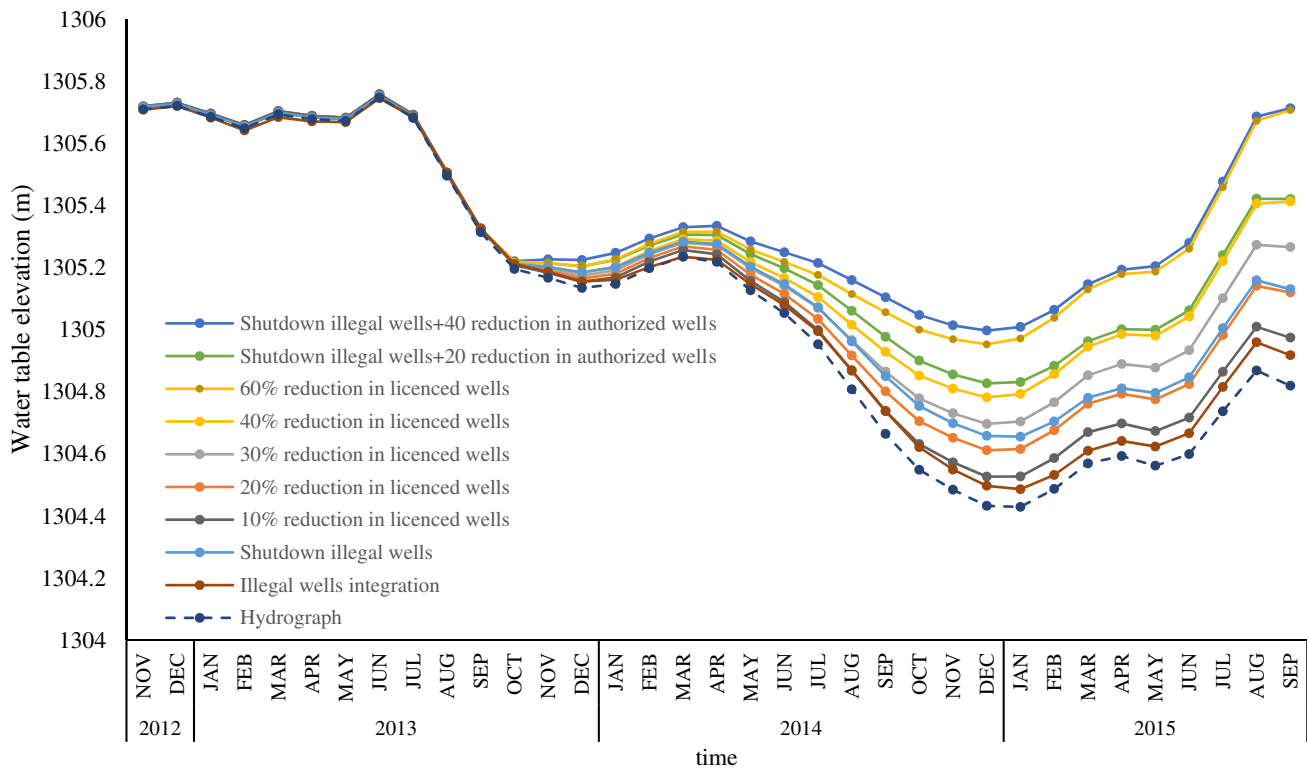


Fig. 19 Comparison of the effectiveness of shutdown of illegal wells with a reduction in the extraction

be prevented. According to the results of the scenarios, it can be concluded that the most effective, least expensive, and most reasonable scenario is to reduce extraction from licensed wells, which requires changes in the cultivation pattern, modernization of irrigation systems, and smartization of wells. In the next step, as farmers live on agriculture and need to exploit the groundwater, though illegally, by application of the last scenario, i.e., integration of illegal agricultural wells, tensions on this aquifer can be reduced, and the current status may be improved. Closing off illegal agricultural wells can be applied as the last scenario among the scenarios discussed here, and the aquifer's status can still be improved. However, in terms of dependency of the livelihood of wells owners on these illegal resources, closing off the wells might not be a successful decision due to ensuing dissatisfaction. Water harvesting by licensed and illegal wells from groundwater resources in most aquifers of the country, such as the study region, is common. Therefore, the scenarios used in this study can apply to similar regions as well as similar problems. The findings of the present study can improve the status of groundwater resource management in the Shabestar Plain aquifer and lead to sustainable development of this valuable resource.

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Data availability The datasets analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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