

Management of an aquifer with an emphasis on the interaction of the aquifer and river using MODFLOW model in Gotvand–Aghili plain, Khuzestan, Iran

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Abstract In recent years, mathematical models are used as efficient tools in the study and management of water resources. Quantitative perception of groundwater flow and knowing the interaction between surface water and groundwater are among the important parameters in water resources management. In this regard, the quantitative model of Gotvand–Aghili Plain groundwater located in Khuzestan Province, in the southwestern part of Iran, has been prepared due to its importance in the agriculture of the region. This study aims to simulate groundwater flow in Gotvand–Aghili Plain using the MODFLOW model to the management of the aquifer and investigates the relationship between the river and aquifer by the Zone Budget method. After the steady-state simulation, the model was calibrated from October 2007 to September 2008 in the unsteady state. After validation of the model, it was used as a management tool to study the different management scenarios and interactions of aquifer–river including the rise and decline of the river water level. The results showed that the riverbank in the north and south of the region is suitable for construction of new wells. The Karun River reach in the study area was divided into seven zones and water balance was assessed in each of them. Results indicate that the river is draining the aquifer in the northern and especially central parts of the plain and recharging it in the southern zones. Aquifer–river exchanges are mostly affected by the river water level fluctuations.

Keywords Zone Budget · Aquifer–river interaction · Gotvand–Aghili plain · Karun River · MODFLOW

Introduction

Due to special weather conditions in Iran, water is one of the most important factors for economic development. The growing need for agricultural products and livestock necessitates water supply and control for such consumptions which requires the suitable management of surface water and groundwater resources. Consequently, an understanding of the mechanism of water exchanges between groundwater and surface water is needed for proper management of water resources (Sophocleous 2002). Optimal utilization of groundwater requires accurate management and supervision, and since excessive groundwater extraction results in a significant drop of groundwater level, the most important issue in the management of aquifers has been to control excessive pumping and different types of pollution. Therefore, it seems necessary to predict the aquifer response to the effects of discharge and recharge on the quality and quantity of groundwater, conduct hydrogeological assessment of the aquifer, and finally ensure its long-term development that in turn will lead to the overall development and widespread use of groundwater models.

Application of mathematical models in the study of groundwater resources has become popular throughout the world since about 1960. Faust and Mercer (1980) introduced mathematical and numerical models in relation to groundwater modeling. Remson et al. (1980). Stephens (1983). and Krabbenhoft and Anderson (1986) used the model in their studies in order to interpret the aquifer. In 1988, McDonald and Harbaugh offered the computer code of MODFLOW. Modeling studies in Iran were carried out in 1969 for the first time by the Food and Agriculture Organization (FAO), and the

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Varamin Plain aquifer was simulated using a mathematical model (Attarzadeh 1981). Tavasoli and Chitsazan (1998) used the finite element model to simulate the Mahyar Plain aquifer. The model was used to evaluate different scenarios of conjunctive exploitation of groundwater and the water delivered from the Zayandeh Rood River to the Mahyar Plain.

One of the most important interactions occurs between river and aquifer. Although the first major simultaneous study of the surface and groundwater resources was attributed to Buras (1961). some scattered studies were conducted since 1940 by researchers such as Theis (1941) and Glover and Balmar (1954).

In the early 1970s, simultaneous studies were conducted using mathematical simulations such as studies of Bittinger (1965) and Young and Bredholm (1972). These interactions that are complex spatially and temporally received great attention recently (Morrice et al. 1997; Cey et al. 1998; Wroblicky et al. 1998; Fleckenstein et al. 2006; Andersen 2009).

Mozafari (2007). Jahromi (2009). Firuzkuhi (2011). and Rahmani (2012) studied the geomorphology, geology, and hydrogeology of the study area with different methods (MODFLOW and artificial neural networks) to simulate groundwater flow in the aquifer. But this research in addition to the simulation of the aquifer also considers the interaction of the aquifer and river by the model.

This research aims to simulate the hydrogeological system of the Gotvand–Aghili Plain aquifer using MODFLOW-2000 code in GMS software, to use the constructed model in aquifer management, and particularly to investigate the exchange of the aquifer groundwater with the Karun River.

Because of unavailability of funds and tools, the investigation on the interaction between the aquifer and Karun River was not carried out in the study area. We focus on the Zone Budget capability of GMS as the first attempt to explore the interaction of the aquifer and the Karun River in the study area.

The model describes groundwater flow in porous media of constant density under non-equilibrium conditions in a heterogeneous and anisotropic medium according to the following equation (Bear 1979):

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

where K_{xx} , K_{yy} , and K_{zz} are the hydraulic conductivities along the x , y , and z directions, respectively. h is hydraulic head, W volumetric flux per unit volume, S_s specific storage coefficient of porous medium, and t is time.

Basic concepts and principal equations of groundwater and surface water interactions

Large-scale exchange of groundwater with surface water is controlled by the distribution and magnitude of hydraulic conductivities, within both the channel and the associated alluvial plain sediments; the relation of stream stage to the adjacent groundwater level; and the geometry and position of the stream channel within the alluvial plain (Woessner 2000). In this respect, there are several models for simulation of the mentioned relationships, though each has its own difficulty

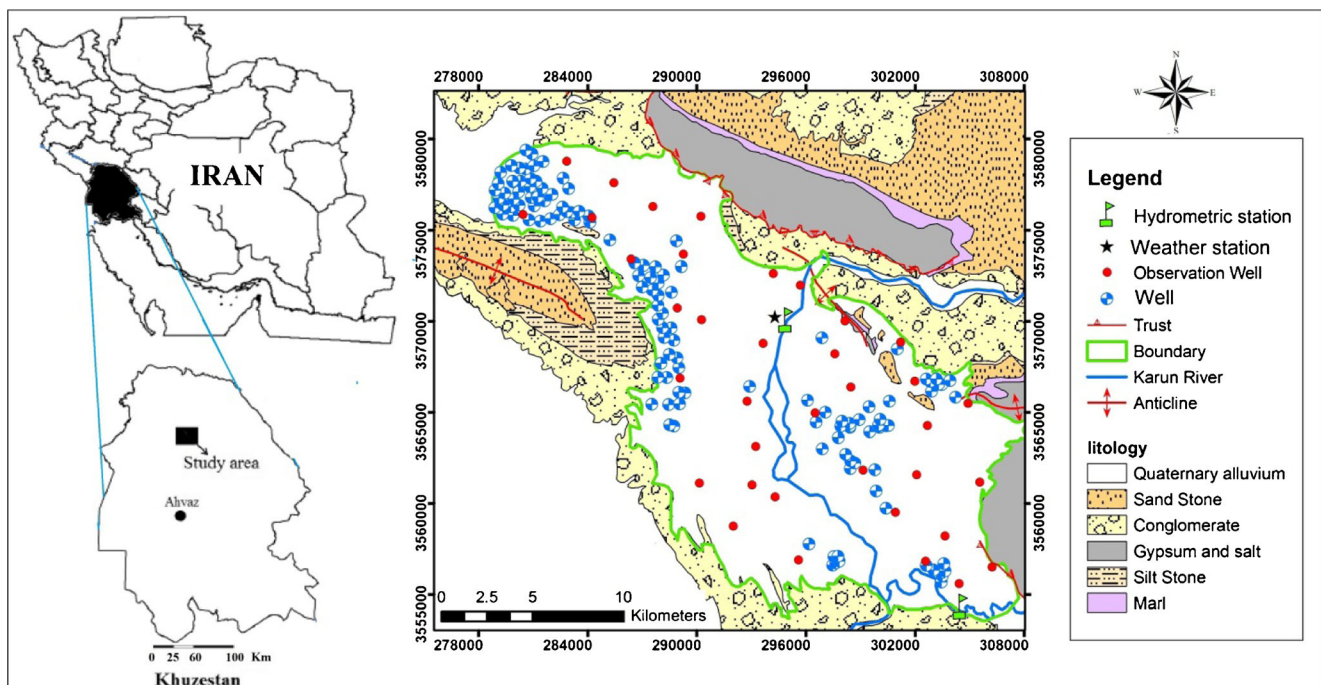


Fig. 1 Location and general map of the study area

and, due to the complexity of the issue, no complete model has yet been developed.

It is generally trying to relate hydraulic conductivity (leakage coefficient of the riverbed) with its associated hydraulic head difference. Based on this, the main equations of interactions are presented in the forms of Eqs. (2) and (3) (Kresic 1997):

$$QRIV = CRIV \cdot (HRIV - h_{i,j,k}) : h_{i,j,k} > RBOT \quad (2)$$

$$QRIV = CRIV \cdot (HRIV - RBOT) : h_{i,j,k} \leq RBOT \quad (3)$$

where QRIV is the flow exchange between the river and aquifer; CRIV is the hydraulic conductivity of the riverbed (conductance) whose values are expressed according to Eq. (4); $h_{i,j,k}$ is the hydraulic head in the aquifer beneath the corresponding node

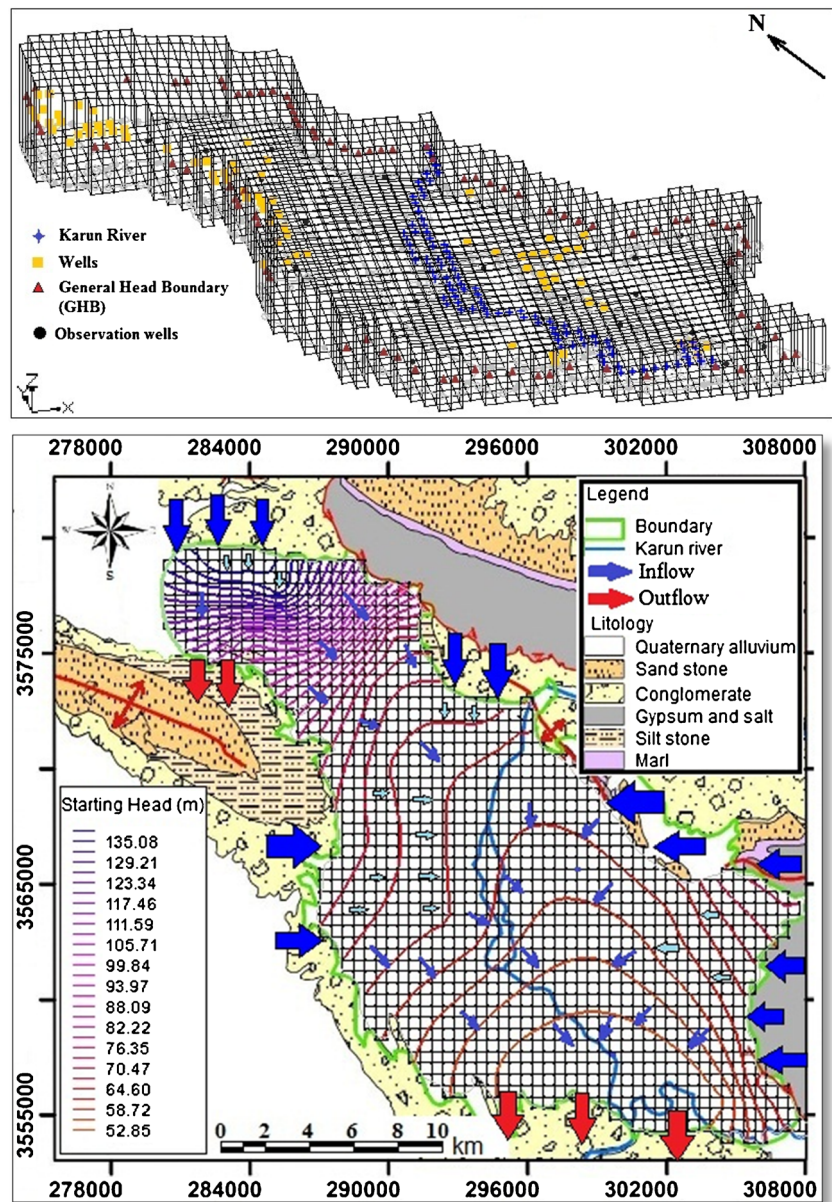
cell; HRIV is the hydraulic head of the river; and RBOT is the elevation of the riverbed bottom.

$$CRIV = \frac{K \cdot L \cdot W}{M} \quad (4)$$

where K is the hydraulic conductivity, W and L are the width and length of the contact area, and M is the thickness of the riverbed.

Several packages with different levels of complexity for modeling river flow have been developed with MODFLOW code. Based on MODFLOW definition, the hydraulic connection between the river and the aquifer exists only where the water table is higher than the base of riverbed sediments. The reciprocal relationship of Gotvand–Aghili Plain groundwater and the Karun River is simulated by determining the hydraulic

Fig. 2 Conceptual model of Gotvand–Aghili plain groundwater with grids, boundary conditions, groundwater level contour map, and geometry of the aquifer



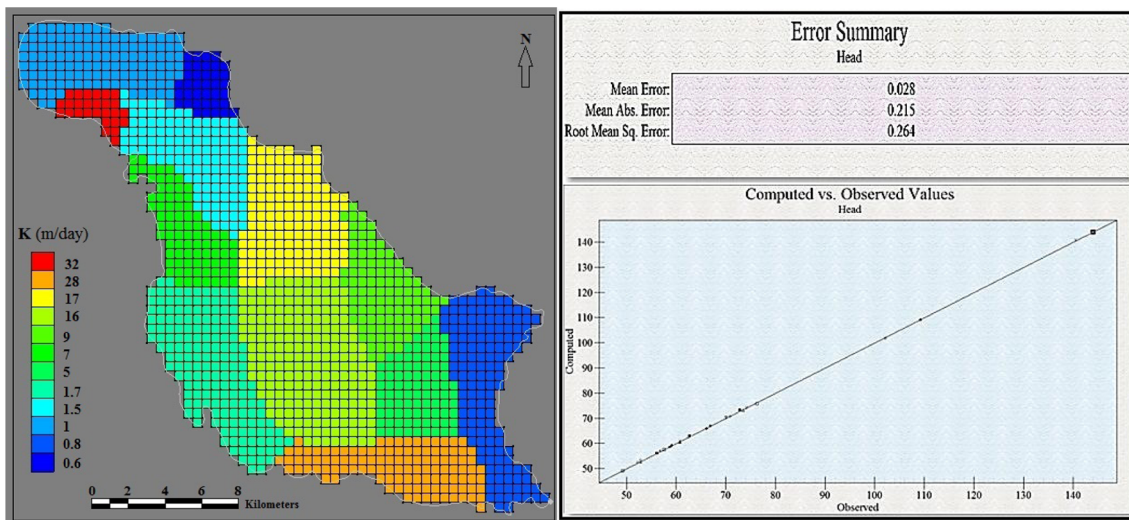


Fig. 3 Value of RMSE at steady-state condition and zoning of calibrated hydraulic conductivity

head in the aquifer boundaries, initial hydraulic head, and river water level, and using Eqs. (1) through (4).

Geographical, geological, and hydrogeological overview

Gotvand–Aghili Plain with an area of approximately 342 km² is located in the north of Khuzestan Province and Shushtar township on the western slopes of Zagros mountain belt with the X coordinate from 278,745 to 308,182 and the Y coordinate from 3,553,588 to 3,579,835 in the UTM coordinate system. Its average elevation is 84 m above sea level. The Karun River passes through the plain where the Gotvand and Aghili areas are located on the western and eastern parts of the plain, respectively. Gotvand regulatory dam and Gotvand Olya dam are located in the upstream portion of the region. The plain is surrounded by Gachsaran, Mishan,

Bakhtiari, and Aghajari geological formations and Lahbry member (Fig. 1).

Sequenced strata in the terraces and cliffs have formed the northern part of the region where the Karun River flows and enters the Gotvand Plain. The average annual rainfall over the study period is 406.7 mm. The highest rainfall occurs in January with the average rainfall of 97.1 mm, and the period of no rainfall is between July, August, and September. The area has a semi-arid climate (Khuzestan Department of Water and Power 2007).

Materials and methods

First, a conceptual model was generated using hydrologic and hydrogeologic data, such as hydraulic conductivity, water

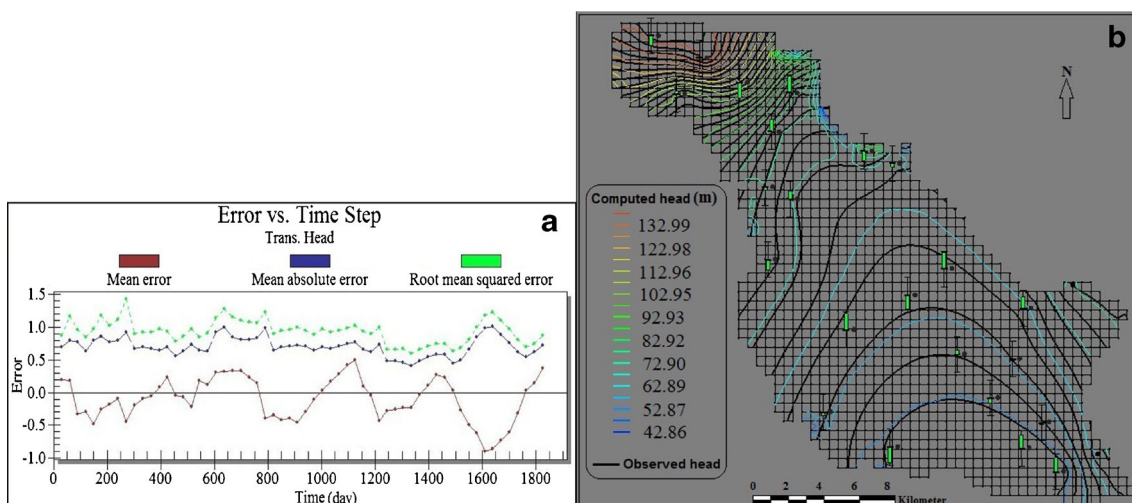


Fig. 4 Model errors at different stress periods during the calibration (a) and a good fit between simulated and measured water levels (b)

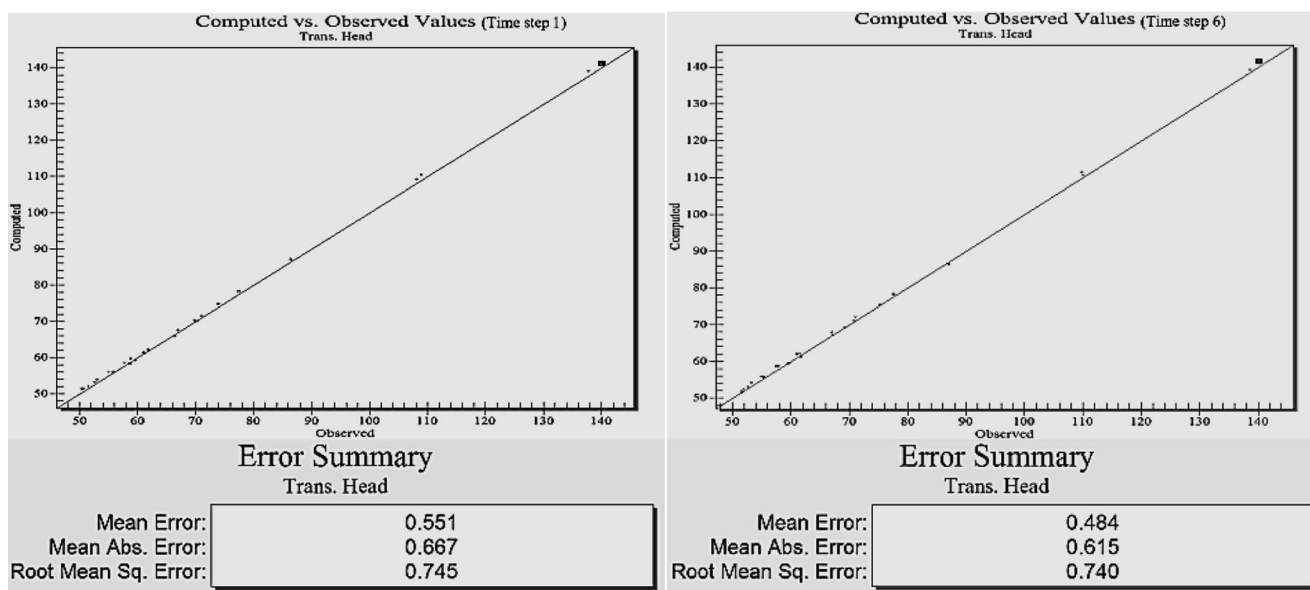


Fig. 5 Value of RMSE at validation state

table level in observed wells, rate of recharge resulting from rainfall and returned water of agricultural wells, discharge by wells, boundary conditions, distribution of geological formations, surface topography of the land, and the aquifer bottom elevation.

A conceptual model was developed by creating and saving data in ArcGIS and providing appropriate structural and exchangeable codes similar to (MODFLOW-2000) simulation code. Then, the overall current condition of the aquifer was evaluated, the hydrodynamic parameters were estimated and optimized, and the quantitative model of the aquifer was produced using the GMS software. In order to characterize the interactions between the river and the alluvial aquifer, the Karun River data, including parameters such as river water level and the river bed elevation data, were obtained from gauging sites and river cross sections. After the calibration and validation of the model, the different management scenarios and the relationship between the aquifer and the river were examined using Zone Budget and through the partial balance. To do so, the Karun River reach in the study area was divided into seven zones and water balance was assessed in each of them.

Model design

Conceptual model Gotvand–Aghili Plain is an unconfined aquifer with a single layer. The geological formations around the plain consist of sedimentary rocks (conglomerate, sandstone, marl, siltstone, and gypsum). The main surface water feature in the watershed is the Karun River. Groundwater flow general direction is from the north, west, and east to the center and south, and the water is discharged to the Karun River. The most important sources of the aquifer recharge are the direct

recharge from precipitation, subsurface flows, and returned water from wastewater and irrigation. The most important sources of the aquifer discharge are pumping wells, subsurface flows, and evapotranspiration (ET). The inflow and outflow boundaries were simulated using the General Head Boundary (GHB) package. Based on the evaporation data of Gotvand weather station, evapotranspiration in areas where groundwater depth is less than 5 m is defined in the model. The river bottom was determined by measured values in the hydrometric station and using topographic maps and Google Earth software.

Surface recharge zones were defined in the model, based on the amount of precipitation in the rain gauge station and the rainfall penetration percentage estimated from the area soil map. Initial values of recharge based on the zoning maps of soil texture and the amount of monthly precipitation were prepared. Therefore, according to heavy and light soil, the percent of the penetration of rain was considered between 15

Table 1 Components and values of Gotvand–Aghili plain water balance

Volumetric budget (* 10 ⁶ (m ³))		
Balance components	Inflow	Outflow
River leakage	25.2	76.78
Wells	–	95.91
ET	–	61.76
Recharge	225.81	–
Head dep bounds	214.65	238.30
Total	465.67	472.77
In–out	–7.09	

Table 2 Components and quantities of the water balance of Gotvand–Aghili plain model, according to two decreasing and increasing pumping scenarios

Balance components	25 % reduction in pumping * 10 ⁶ (m ³)	10 % increase in pumping * 10 ⁶ (m ³)
In		
River leakage	24.76	25.38
Head dep bounds	210.45	216.36
Recharge	225.81	225.81
Total in	461.02	467.56
Out		
Wells	71.93	105.50
River leakage	78.37	76.15
ET	61.97	61.68
Head dep bounds	239.33	237.92
Total out	451.62	481.26
In–out	9.39	–13.70

and 25 %. But due to the abundance of the returned water from agricultural and irrigation networks and its uncertainty in the study area, the final value of the recharge was calibrated in the model. Hydraulic conductivities, estimated from well logs and previous studies, were used as an initial guess for the calibration. Exploitation wells in the model were applied monthly on the basis of operating time and pumping discharge of the wells

provided by the Khuzestan Department of Water and Power. There are 36 piezometers in the study area, from which the 25 active ones were applied in the simulation period.

The conceptual model of Gotvand–Aghili Plain aquifer was designed in GMS software using the geological, geophysical, hydrological, and hydrogeological data (Fig. 2).

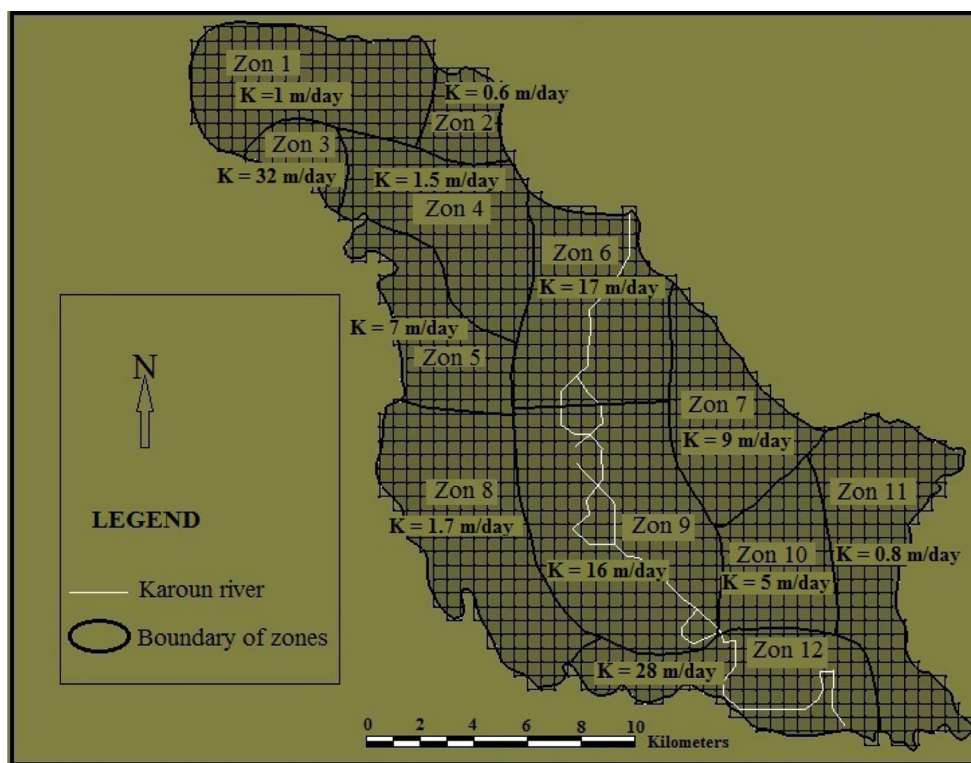
After preparation of the conceptual model, the study area was gridded into 64 columns and 58 rows in block center type with 500 m length and width. Inflow boundaries of the model include northern, northwestern, northeastern, western, and eastern parts of the model area. Outflow boundaries include the central and southern parts of the model area.

Model calibration and validation

After preparation of the conceptual model, a steady-state condition has been considered in September 2007. The calibration period was selected based on 5 years of available data. Trial and error calibration was used to adjust the hydraulic conductivities during the sequential model runs to obtain the best match between calculated and observed piezometer heads. Figure 3 shows the results of the calibration model in steady state.

Transient state Based on the plain unit hydrograph and according to the available data, the model was calibrated from September 2007 to August 2012 in 1825 days in 60 stress

Fig. 6 Zoning of the study area to determine the zone budget



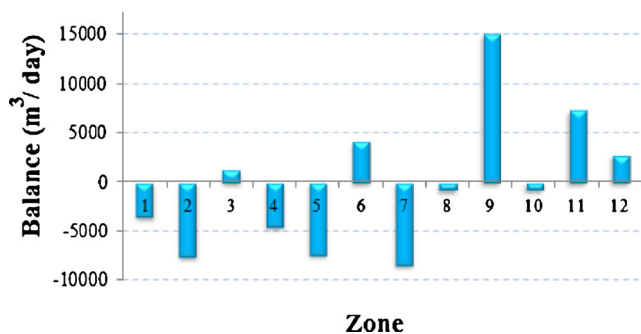
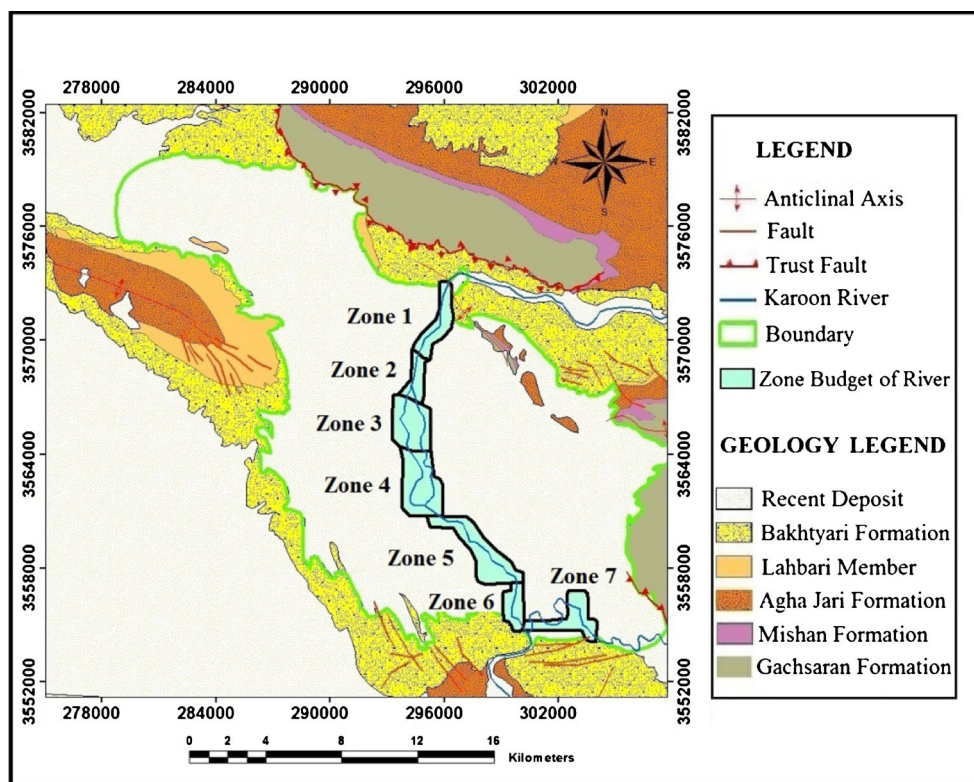


Fig. 7 Average balance in different zones of the region

periods, and was simulated using MODFLOW-2000 in the GMS software. Figure 4a shows different errors of the model during the 60 stress periods of calibration, and Fig. 4b shows good fit between simulated and measured water levels in stress period 1 in the study area.

Validation Model validation is in reality an extension of the calibration task. There are several approaches to validate a model; perhaps the most effective procedure is to use only a portion of the available record of the observed values for validation. The validation was performed from September 2012 to February 2013 in six stress periods. Reasonable agreement between the observed and simulated water tables in the observation wells for stress periods 1 and 6 was obtained as is evident from Fig. 5.

Fig. 8 Balance zoning to determine the exchange rate of river and aquifer



After the validation period, the model balance was calculated using the Budget package. Based on the results, the groundwater balance in the modeled period (from September 2007 to August 2012) shows the negative volume change of about 7 million m³ in the reservoir (Table 1).

Results and discussion

Management of Gotvand–Aghili Plain aquifer

The growing need to use groundwater resources and the increasing trend of digging wells along with the occurrence of drought create severe stresses on the aquifer. Therefore, it is necessary to study the methods of prevention and reduction of probable irreparable damages and the other factors that affect the aquifer. For better management of the aquifer, it is possible to predict the effect of various hydrological phenomena using the calibrated model. To do so, the model was run in two scenarios of increased (10 %) and decreased (25 %) pumping and the effects of pumping changes were compared with the normal situation of the region. Table 2 shows the balance of running the model with these two scenarios. As shown in Table 2, the change of pumping from the wells will cause some changes in the other parameters of the balance as well. Considering the results, it is clear that surface recharge due to precipitation and return flow from irrigation network, and the

Table 3 Budget rate of the river zones 1 through 7 in 2007–2012

Budget of zones (* 10 ³ (m ³ /day))			
Zone number	Inflow (river to aquifer)	Outflow (aquifer to river)	Exchange volume
1	66.84	250.78	-183.94
2	150.20	490.46	-340.26
3	292.58	952.40	-659.81
4	56.83	265.75	-208.91
5	253.79	66.74	187.04
6	2.35	163.99	-161.63
7	4.97	339.71	-334.73

Karun River are the most important inflow parameters to the aquifer.

The outflow from the boundary and then the evapotranspiration are the most important outflow parameters of the aquifer. As it is observed, among the outflow parameters of the balance, the wells have lower effects on the water balance. According to this finding, the new wells can be constructed or the older wells can be developed in proper areas if necessary.

For further investigation of the aquifer condition, the partial balance was examined in various sectors. To do so, the average balance per model period (from 2007 to 2012) was calculated for each one of the calibrated hydraulic conductivity zones of the model using the Zone Budget package in GMS software (Fig. 6). As it is observed, most of the zones have negative balance and the conclusion should be considered in the management of the aquifer. In this way, the zones with

positive balance can be determined for the construction of new wells (Fig. 7). Zones 3, 6, 9, 11, and 12 have positive balance. Among them, zones 6 and 9 are more secure for the construction of wells due to further hydraulic conductivity and being located in the riverbank.

Aquifer–river relationships

The relationship between the alluvial aquifer system and river is affected by the spatial distribution hydrofacies of river located at the boundaries of the river and its underlying aquifer (Woessner 2000). In modeling studies of the river–aquifer relationships, regional impact of water resources management and conjunctural use of water resources should be accounted for (Reichard 1995; Onta et al. 1991; Wang et al. 1995). The average regional thickness of riverbed sediments and hydraulic conductivities used in large-scale models affect the river–aquifer relationships (Anderson and Woessner 1992).

To evaluate the relationship of the Gotvand–Aghili aquifer with the Karun River based on the constructed model, the River package was used. For this propose, the Karun River was divided into seven zones using the Zone Budget package. This package calculates the water balance in smaller zones in the model area. To determine the location of recharge water from the Karun River to Gotvand–Aghili Plain and discharged water from the aquifer (to Karun River), the river reaches were divided into seven zones (Fig. 8).

After defining the parameters required for the model, the exchange rate of the river and aquifer was calculated for each of the seven regions. Table 3 shows the modeled water balance in 2007–2012.

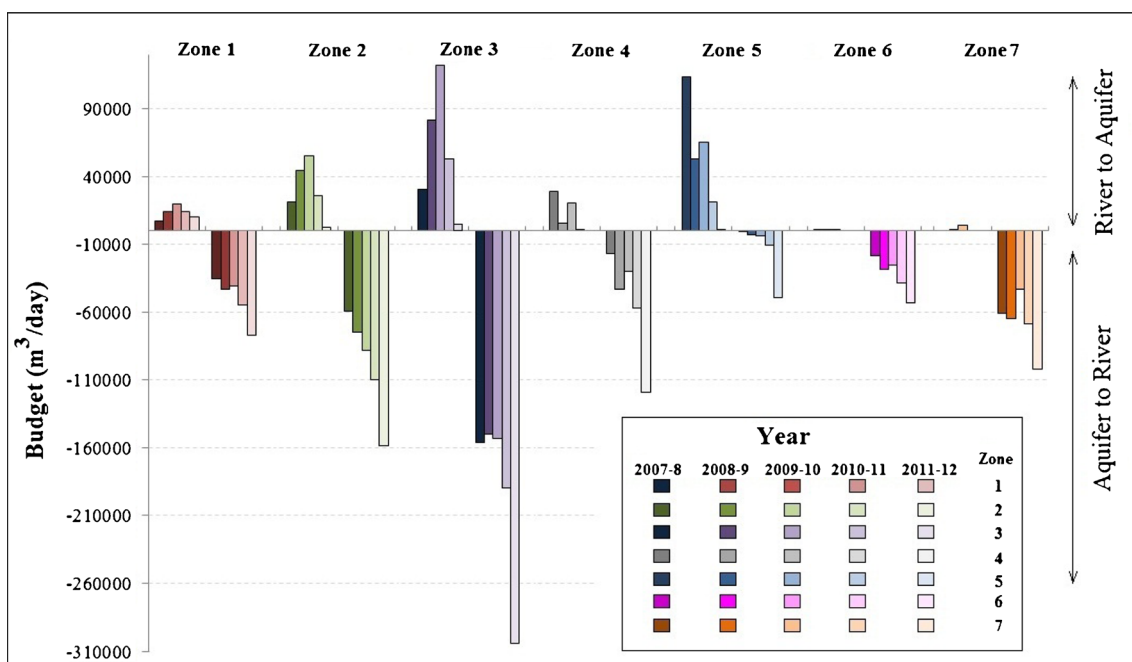


Fig. 9 Time series of inflow–outflow balance for the seven zones in 2007–2012

Table 4 Modeled prediction of volumetric partial water balance due to the river level rise in the fifth year

Budget of zones (* 10 ⁶ (m ³))			
Zone number	Inflow (river to aquifer)	Outflow (aquifer to river)	Exchange volume
1	1.214	0.0236	1.190
2	3.423	0.103	3.320
3	4.807	0.477	4.329
4	1.047	0.0228	1.0243
5	4.241	0	4.241
6	0.2148	0.1751	0.0397
7	1.382	0.03274	1.349

By drawing the inflow and outflow balance of each of the seven zones as time series, recharge and discharge areas of the system in different years were identified (Fig. 9). Using this diagram, sensitive and vulnerable areas of the aquifer and river can also be predicted. In this figure, each of the columns corresponds to a year in the model for each of the 5 years of the modeling period. For a relative comparison of the inflow and outflow, the values are shown as a combined term. Inflow values are shown as “river to aquifer” and outflow values as “aquifer to river” together with the number of the zone.

According to this figure, the maximum outflow of the aquifer to the river occurs in the central zones of the plain, especially in zone 3 with 305,000 m³ per day in 2011–2012 (Fig. 9). This trend is also visible with less intensity for the surrounding zones (1, 2, and 4). According to Fig. 9 and Table 3, the largest recharge of the aquifer by the river occurs in zone 5, which is in accordance with the groundwater level map. By drawing the inflow and outflow values together and comparing them, it is found that the Karun River is draining the aquifer in most areas. Zone 5 in the south of the plain has a positive balance and recharges the aquifer.

Due to the increasing demand in the use of underground water resources, the growing trend of well drilling, droughts or wet periods, and the interaction of groundwater resources and surface water in different management scenarios should be evaluated. Therefore, the interactions of Gotvand–Aghili Plain aquifer groundwater and the Karun River were evaluated in the following two scenarios: (1) river water level rise due to flooding and release of water from the Gotvand dam and (2) decline due to the effect of the dam regulation.

River water level rise due to flooding and release of water from the Gotvand dam

During recent years, the water level in the Karun River has been subject to different stresses due to the construction of dams upstream. One of these stresses is the water release from the dam to control the volume of water in the dam reservoir in flooding seasons. Based on this stress, the river water level rises and its water exchanges with the aquifer are modified accordingly. Modeling is an appropriate tool to predict the effect of these stresses. To predict the interactions between the aquifer and the river due to the river water level rise, the water level data from the 2003–2011 periods were assessed and the water level belonging to 2005–2006 was selected as maximum water level and used in the model. The modeled prediction of volumetric partial water balance due to the river level rise is shown in Table 4.

Table 4 shows that the increase in the river water level decreases the negative water balance in the discharged areas and increases the positive water balance in recharged areas that can be associated to the hydraulic gradient changes.

As Fig. 10 shows, due to the river water level rise, in addition to the increase in recharging effects of zone 5, the other zones which formerly had the discharging effect also recharge the aquifer. Especially, zones 2 and 3 which were also drained by the aquifer had the recharging effect in the months with the

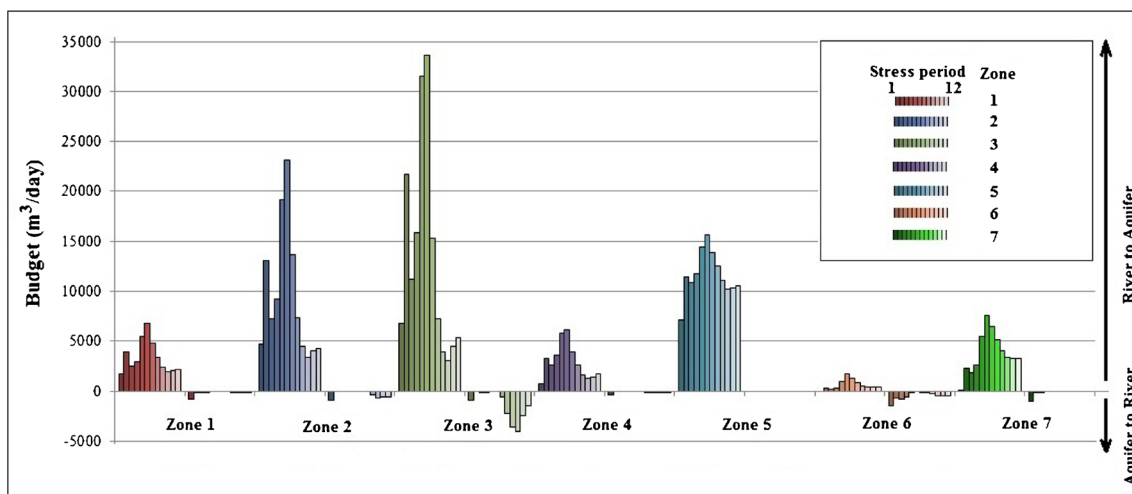


Fig. 10 Monthly time series of inflow–outflow balance for the seven zones due to the river water level rise in the fifth year

Table 5 Modeled prediction of volumetric zone budget due to the river level decline in the fifth year

Budget of zones (* 10 ⁶ (m ³))			
Zone number	Inflow (river to aquifer)	Outflow (aquifer to river)	Exchange volume
1	0.2883	2.624	-2.336
2	0.0447	5.267	-5.223
3	0.1134	9.858	-9.745
4	0	4.085	-4.085
5	1.928E-05	2.082	-2.082
6	0	1.772	-1.772
7	0	3.884	-3.884

highest water level in the river (stress periods 5 and 6). As depicted in the figure, although zone 3 had the maximum amount of recharge, it had the overall highest amount of aquifer discharge to the river. This scenario shows that the relationship between the aquifer and the river is significantly dependent on the changes in the hydraulic head between the river and the aquifer such that an increase in the river water level changes the flow direction permanently or in some periods.

River water level decline due to the effect of the storage in Gotvand dam

Decline of river water level due to regulation of water in the dam reservoir is one of the most important stresses posed on the river. To predict the interactions between the aquifer and the river due to the river water level decline, the Karun River minimum water levels from 2003 to 2011 were used and minimum river water level belonging to 2010–2011 was selected.

The water balance of all seven zones that buffered the river shows the increase in aquifer discharge to the river that is due

to the increase of the hydraulic gradient, from the aquifer to the river (Table 5). As Fig. 11 shows, due to the river water level decline, in addition to the increase in discharging effects of zones 1, 2, 3, 4, 6, and 7, zone 5 which formerly had the recharging effect also discharges the aquifer. So, with a declining river water level to minimum, all zones acted as drains.

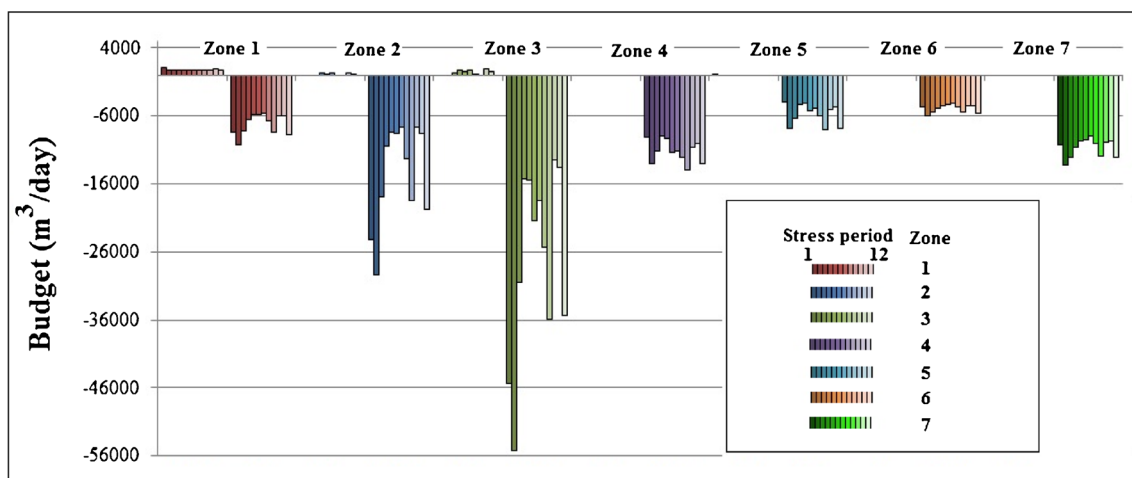
Conclusions

The results show that in the modeled years, infiltration has the highest share (59 %) of the balance among other inflow factors. The boundary inflow with 38 % and the inflow from the river 3 % constitute the rest of the inflows. Among the outflow factors, boundary outflow has the highest share (56 %); evaporation, especially in the eastern part of the river, has 24 % share; and outflow from the river and discharge by wells each has 10 % share.

The small share of the river outflow compared to other balance factors can be associated with the recent droughts; the impact of upstream dams, especially Gotvand regulatory dam and Gotvand Olya dam; and the resulting decline in the river water level.

The results of management scenarios and investigating partial balance at different parts of the aquifer showed that most of the zones have a negative balance and should be cared for in the management and operation of the aquifer. Among the 12 zones investigated in the region, zones 3, 6, 9, 11, and 12 have a positive balance. Among them, zones 6 and 9 are more confident for the construction of wells due to further hydraulic conductivity and being located on the riverbank.

The results of the model and balance analysis in different scenarios show that the Karun River drains the aquifer in the northern and especially the central part of the Gotvand–Aghili Plain, while in the southern and southeastern parts of the plain recharges the aquifer. Zones 1, 2, 3, 4, 6, and 7 drain the river

**Fig. 11** Monthly time series of inflow–outflow balance for the seven zones due to the river water level decline in the fifth year

and zone 5 recharges it. Based on various scenarios, the hydraulic head of the river and aquifer had the highest effect on the system interactions. The most influential factor on the hydraulic head was flood persistence and river water level rise. In this case, the specified zone in the center and north of the plain (especially zone 3) that previously had the draining effect changed function during rainy seasons and even recharged the aquifer. With a declining river water level, all zones acted as drains and even zone 5, which formerly had the recharging effect, also discharged the aquifer.

The results show that the impact of hydraulic structures such as Gotvand dam on the exchanges between the Gotvand–Aghili Plain aquifer and the Karun River is more than climate and other human activity factors. These human factors with instant tensions affect the natural system of aquifer–river much faster than climate factors and effect the flow direction change.

This study shows that groundwater modeling is a good, simple, inexpensive tool to examine the interaction between the aquifer and river. Therefore, the focus of this research was using the zone budget capability of GMS to explore the interaction of the aquifer and the Karun River in the study area. The methodology is simple and can be helpful for decision-makers in areas such as water pollution and water allocation in the study area and other regions.

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