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Original paper

Use of a mathematical modeling approach to investigate interaction between groundwater and river: A case study on the north of the Dezful-Andimeshk plain, southwest of Iran

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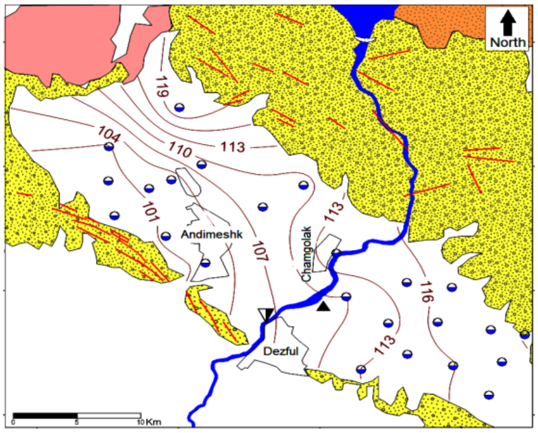
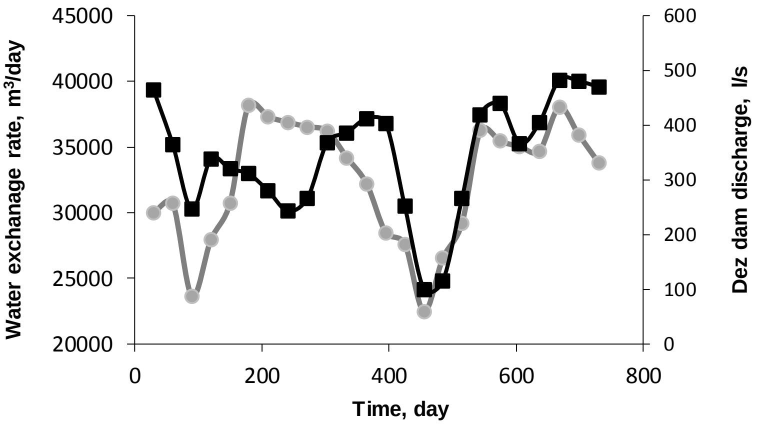
GRAPHICAL ABSTRACT





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ABSTRACT

Alluvial rivers interact mostly with underlying groundwater bodies. These interactions that varies spatially and temporally, have recently received more attentions. This paper aims to evaluate the interaction between groundwater and surface water along the Dez river in the north part of the Dezful-Andimeshk district through developing a numerical simulation. For this purpose, the groundwater flow and river- groundwater interaction were simulated using a mathematical model in MODFLOW/GMS environment. The WetSpass model was used to estimate the groundwater recharge. The cluster analysis method, also, was utilized to identify the different zones of aquifer hydraulic characteristics. The results show that the Dez river has a losing connected nature and recharges groundwater. The river recharge to the aquifer was about 12 MCM during the 2013 and 2014. This recharge varies spatially and temporally and its maximum amount occurs during the 2014 March to June. Furthermore, the recharge rate was affected by the water release pattern from the Dez dam and topographic characteristics of the riverbed sediments. So that the maximum water exchanges occur in areas near the Chamgolak town and Dezful city with an average rate of 3.2 MCM per year.

1. Introduction

The hydrologic cycle describes the movement of water on Earth (Joo et al. 2018). Groundwater-surface water resources are two main components of the hydrologic cycles. From ancient times, the rivers and groundwater resources have been considered as the vital sources of water supply (Roholamin Kasmaei et al. 2017). Groundwater-surface water interaction is one of the most common types of water exchanges in hydrologic cycle. During the recent years, special attentions have been paid to the integrated water resources management, in which the knowledge on groundwater – surface water interaction is very important. Understanding of this interaction is important for determining safe levels of groundwater allocation and environmental river flows and for identifying transportation of contaminants (Guggenmos et al. 2011). Currently, many research centers have been concentrated on mechanisms and consequences

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of the interaction between surface water and groundwater resources around the world. Various field methods such as seepage meters, mini piezometers, thermal sensors and natural and artificial tracers were developed as a subsequence of these efforts. All of these methods suffer from limitations associated with their spatial and temporal scales (Cremeans et al. 2018).

In some cases, surface water can gain from the groundwater and in the other cases the surface water recharges the groundwater (Winter et al. 1998). River-groundwater interaction is one of the most important types of surface water–groundwater interactions. These interactions, which are spatially and temporally complex (Harish Kumar and Nagaraj. 2018), received recently great attentions (Andersen. 2009; Barthel and Banzhaf. 2016). The mechanism of groundwater-river interaction is still poorly understood (Kalbus et al. 2006). Many factors are involved in these water exchanges. For example, the extraction wells near the river can cause the water flow into the underlying aquifer (McCarthy et al. 1992; Rosenberry and Labaugh. 2008).

On the other hand, the quality of groundwater and surface water is also influenced by abovementioned interactions (Rautio et al. 2015). Generally, some detailed hydrogeological studies are needed to understand the water exchanges between a river and groundwater (Sophocleous. 2002). In a general view, rivers are classified in two main types: gaining rivers and losing rivers. Groundwater flows toward the rivers in gaining rivers. While, the river water moves toward the groundwater in losing rivers (Chen et al. 2013).

Also, depending on the saturation conditions between riverbed and the underlying groundwater body, rivers are classified in two major types: connected river and disconnected one (Vazquez-Sune et al. 2007). In a connected river, a saturated media exists between the river and underlying groundwater body (Fig. 1a-c). Whereas, that layer is unsaturated in disconnected losing rivers (Fig. 1d). Goundwater modeling is one of the most commonly used techniques in interpretation of groundwater systems. Groundwater models are interesting from scientific and water resource management point of view (Sanz et al. 2011). Various empirical, conceptual and numerical modeling techniques have been recently developed for the study of river–groundwater interaction (Barthel and Banzhaf. 2016). Each modeling approach has its specific strengths and limitations and no model is efficient for all situations (Ivkovic et al. 2009). The selection of an appropriate model depends on the field conditions and data availability (Jing et al. 2018). Since 1983, the most frequently used mathematical model for study of the surface water and groundwater interaction is MODFLOW (Harbaugh et al. 2000). MODFLOW is a finite-difference numerical model, which contains various stream flow packages (Brunner et al. 2010). This model has a river package, simulating the flow between a river and underlying aquifer. Other MODFLOW packages simulating the flux between river and groundwater are stream package and stream flow routing one (Prudic. 1989). As the third largest river in Iran, the Dez river is the most important surface water resource in the Dezful- Andimeshk district. This river plays a vital role in water supply and agricultural development of Khuzestan province. In present study, the water exchanges between Dez river and Dezful–Andimeshk aquifer have been investigated using a mathematical modeling approach. This study has applied a combination of statistical methods and hydrological and groundwater modeling techniques to assess the groundwater-river interaction. For the first time, this study used cluster analysis for identification of the spatial distribution of the aquifer hydrodynamic properties. A relatively new method was also used for identification of the spatial distribution of the river conductance based on the slope of riverbed sediments. In addition, the WetSpass hydrologic model was uesd for the estimaion of groundwater recharge component of the MODFLOW model. The main purpose of this study is to update our knowledge about the river-groundwater interaction in the Dezful-Andimeshk area.

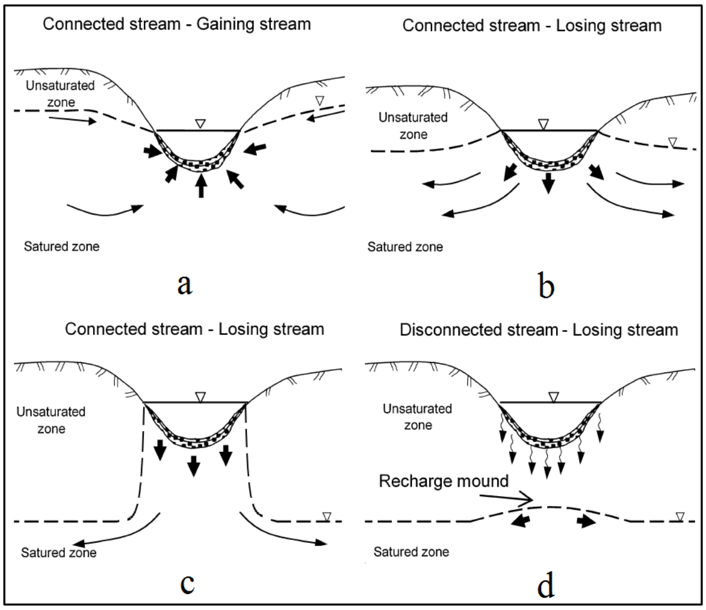

Fig. 1. Common types of hydraulic connection between a river and groundwater (modified from Winter et al. 1998; Vazquez-Sune et al. 2007).

2. Materials and methods

2.1. Study area

The Dezful-Andimeshk area is located in the north of Khuzestan province, south west of Iran, between the latitudes 32°00′ and 32°35′N and longitudes 48°10′ and 48°35′E. Its area is about 479.8 km^2. The Dez river is the most important surface water body in the Dezful-Andimeshk district. The mean discharge of the river is 202 m^3/s in Dezful hydrometric station (near the Dezful city).

The most important geological units in the study area are including Aghajari and Bakhtiyari formations, Lahbari member and quaternary alluvial deposits (Fig. 2). The Bakhtiyari formation mainly consists of conglomerate with sandstone lenses. The erosional products of Bakhtiyari formation contain coarse sediments with high permeability (Chitsazan et al. 2015). The Aghajari formation, in the northeast of the study area, includes sandstone with marl, gypsum and siltstone inter-layers. The Lahbari member also consists of siltstone, gypsum, marl and sandstone in the north west of the Dezful-Andimeshk area. These two latest lithological units (Aghajari formation and Lahbari member) have low permeability. Alluvial deposits are mainly composed of gravel, sand, silt and clay. These coarse-grained and well sorted sediments have high permeability and form a rich aquifer in the study area. Dezful-Andimeshk district includes an unconfined aquifer with an average thickness of 100 meters (Shahsavari et al. 2013). The average depth to groundwater is about 25 meters. Groundwater flows from the north and northeast to the southwest. There are 450 extraction wells in Dezful- Andimeshk area with an average pumping rate of 34 L/s, which more than 90 % of them are used for the agricultural crops irrigation. During the recent years, the groundwater level has shown a decreasing trend. The average amount of groundwater level withdrawal is about 1.4 m annually (Faryabi. 2014).

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2.2. Study method

The methodology of this research consists of three steps. At first, the required data for the modeling process were prepared. In second step, groundwater system was simulated using the MODFLOW model. The numerical model results, eventually, were applied to evaluate the temporal and spatial variations of the Dez river and groundwater interaction.

2.2.1. Step 1: Preparation of the required data

The most important hydraulic parameters in mathematical model generation include the hydraulic head data, pumping rates, aquifer hydrodynamic coefficients and the aquifer recharge rates. The hydraulic head data were measured, using a network of observation wells. As shown in Fig. 2, 24 observation wells have been established in the study area over the recent years, which their water table is measured monthly. The pumping rates of extraction wells were also measured by the Khuzestan Water and Power Authority (KWPA). The spatial distribution of the aquifer hydrodynamic properties is carried out in two steps: At first, the different zones of hydraulic properties were identified, using the water table data. These data were grouped, using cluster analysis method. The Ward clustering method (Ward. 1963) was used for the observation wells grouping. According to the cluster analysis results, the observation wells, categorized into five groups (Fig. 3). In other words, the aquifer was divided into five zones with different hydraulic properties. The amounts of hydraulic conductivities and specific yields were assigned to the defined zones afterward, based on the pumping test results and prior studies by the KWPA.

Fig. 4 shows the areal distribution of hydraulic conductivity and specific yield in the study area.

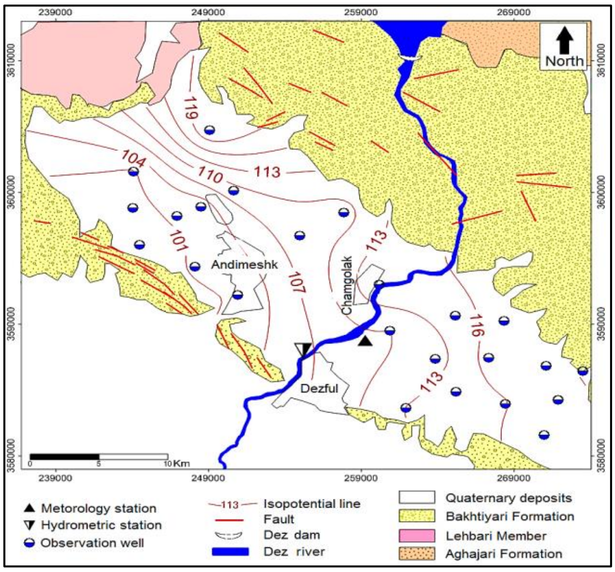

Fig. 2. General map of the study area.

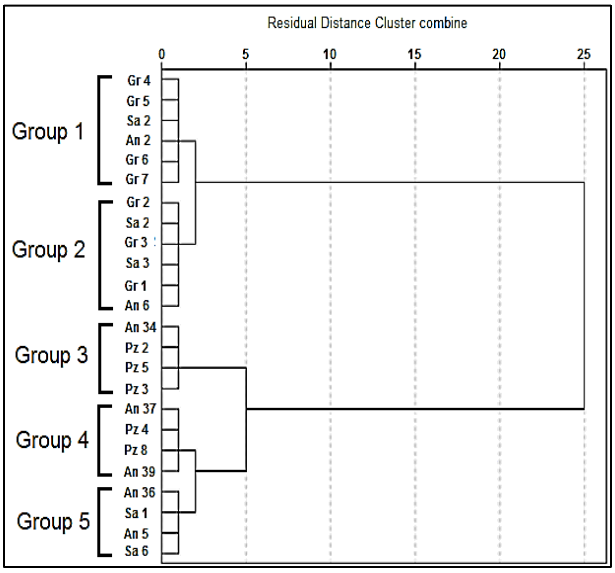

Fig. 3. Dendrogram resulting from cluster analysis of water table data.

Estimation of groundwater recharge is one of the most challenging issues for hydrogeologists. In recent years, several methods have been developed for this purpose such as chloride mass balance, water level fluctuation method, water balance calculation and groundwater modeling. In the present study, The WetSpass model was used for the estimation of groundwater recharge. This model is a useful technique for the surface runoff, groundwater recharge and evapotranspiration evaluation (Batelaan and De Smedt. 2001). The estimated recharge is used as an input parameter to MODFLOW model (Batelaan and Woldeamlak. 2003). In WetSpass model, the total water balance of a cell is calculated, based on the following equations (Batelaan and De Smedt. 2007).

$$ET_{raster} = a_v ET_v + a_s E_s + a_o E_o + a_i E_i \tag{1}$$

$$S_{raster} = a_v S_v + a_s S_s + a_o S_o + a_i S_i \tag{2}$$

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$$R_{raster}= a_vR_v+ a_sR_s+ a_iR_i \tag{3}$$

where, $E_{Traster}$, S_{raster}, R_{raster} are the evapotranspiration, surface runoff and groundwater recharge respectively, while, a_v, a_s, a_o and a_i are the components of vegetated, bare-soil, open-water and impervious areas respectively. In the present study, input data to the WetSpass model includes precipitation, temperature, potential evapotranspiration, wind speed, soil type, land use, topography, slope and depth to groundwater table. Spatial distributions of climatologic data such as precipitation, temperature and wind speed were determined using the data of climatologic stations located around the Dezful – Andimeshk district.

For this purpose, the mathematical relation between the amounts of climatologic parameters (precipitation, temperature and …) and the heights of climatologic stations were determined. The climatologic parameters spatial distribution maps, then, have been prepared, using these mathematical equations and Digital Elevation Model (DEM) of the study area. Also, the potential evapotranspiration was calculated, using the Penman-Monteith method. The land use map was prepared, by the satellite images of Google Earth software. Topographic and slope data were extracted from the DEM. The soil types were determined by the soil map, which had been previously prepared by the Khuzestan Natural Resources Organization. The spatial distribution of depth to groundwater table was obtained from the observation wells data. The groundwater recharge was estimated afterward. Fig. 5 shows the spatial distribution of groundwater recharge. As Fig. 5 shows, the groundwater recharge varies between 47.11 to 191.82 mm/year. These values were applied as the primary values of surface recharge in the groundwater modeling process.

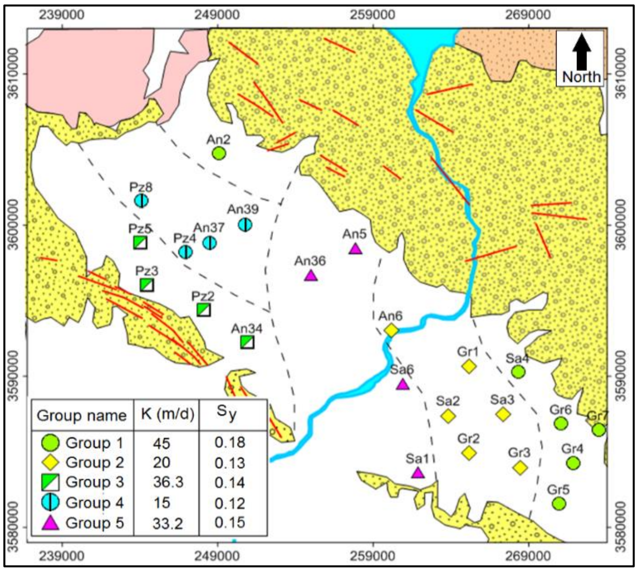

Fig. 4. Spatial distribution of hydraulic conductivity and specific yield.

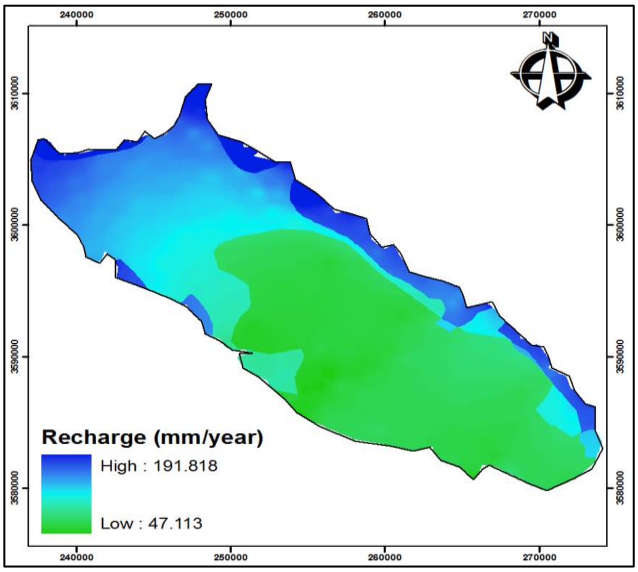

Fig. 5. Spatial distribution of groundwater recharge in the study area.

2.2.2. Step 2: Development and calibration of the mathematical model

The groundwater system was simulated using the MODFLOW model. The GMS (groundwater modeling system) interface is selected for this purpose. The MODFLOW model simulates the groundwater flow based on the following equation (Kresic 1997).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \tag{4}$$

where, K_{xx}, K_{yy} and K_{zz} are the values of hydraulic conductivity along the x, y and z axes [L/T], h is the hydraulic head [L], W is the volumetric flux of groundwater sources and sinks per unit volume [1/T], S_s is specific storage [1/L] and t is time [T].

The conceptual modeling procedure, here, was applied to develop the numerical model. The modeling approach follows the modeling protocol that proposed by the Anderson and Woessner (1992). This protocol includes the model design, calibration, sensitivity analysis, verification, prediction and post audit. The groundwater system in this study was defined as a one-layer unconfined aquifer, whereby the thickness of the saturated layer varies from 90 to 210 m. The three dimensional block- centered grid model, representing the groundwater system, has 11828 cells. With respect to the groundwater flow direction and available hydrogeologic data, the borders of the model domain were selected as general head boundaries (GHB). The Dez river, on the other hand, was simulated using the river package (RIV package).

To simulate the interaction of groundwater and river, the river characteristics such as stage, bed elevation and conductance are considered. The stage and bed elevation were obtained from the river transverse profiles, which have been prepared by the KWPA (2010). The river conductance can be estimated as follow (Paricio et al. 2010).

$$C_e = \frac{K_s.L.W}{M} \tag{5}$$

where, C_e is the river conductance [L2/T], K_s is the riverbed hydraulic conductivity [L/T], L, W and M are river length, width and riverbed thickness [L] respectively. The field experiments show that the riverbed hydraulic conductivity has a magnitude 1-3 times less than the aquifer conductivity (Larkin and Sharp. 1992, Calver. 2001). In groundwater modeling studies, the river conductance is usually estimated based on expert knowledge and it will be adjusted in the calibration process. The riverbed conductance, here, has been estimated, applying the Paricio method (Paricio et al. 2010). It has been based on research of Dade and Friend (1998), which relates the riverbed slope to its grain size as follow (Dade and Friend. 1998).

$$S \approx \frac{\theta_i.R.d}{M} \tag{6}$$

where, S is riverbed slope, θ_i is the shields parameter depending on the type of sediment transport (suspended load, mixed load and bed load), R is the density of sediment particles and d is mean grain size of riverbed sediments. According to Eq. 6, higher slopes lead to coarser sizes of sediments in the riverbed and thus a lower resistance to water exchange between river and groundwater. If Eq. 5 and Eq. 6 be combined, a linear relationship between riverbed slope and the river conductance will be obtained (Paricio et al. 2010). This approach was used to divide the Dez river to different zones of conductance, depending on the slope of riverbed sediments. The river conductance for these zones (Table 1) was assigned according to Calver (2001). In this table, the riverbed conductance is presented per unit length. That is, the values of K_s. W/M were applied to the MODFLOW model. In this study, the numerical model was calibrated using the trial and error method. Aquifer hydraulic conductivity, specific yield and river conductance were adjusted in the calibration process. The calibration target was set to have an error interval of ±1.0 m. Also, the groundwater flow was simulated for 2013 to 2015. The 2013-2014 time period was considered for the model calibration. While, the model verification period is 2014 to 2015 time step. The modeling stress period were monthly considered, due to the monthly records of water Table.

Fig. 6 shows the areal distribution of hydraulic heads at the end of the calibration periods. Also, the computed versus observed heads have been shown in Fig. 7. As shown in these figures, the constructed model successfully simulates the real aquifer behavior. The amounts of mean error (ME), mean absolute error (MAE) and root mean square error (RMS) for the simulation period are 0.23, 0.63 and 0.7 respectively. In the verification period, the prepared model also showed similar capabilities in the simulation of groundwater system behavior (Fig. 7).

3. Results and discussion

3.1. Modeling results

Calculation of the water budget is one of the most common results in numerical simulation of groundwater systems. The simulated water budget has been shown in Table 2. As it showed, the aquifer storage decreased about the 87 million cubic meters (MCM) during the 2013 to 2014. Also, the river recharge to the aquifer was about 12 MCM in same period.

Table 1. Assignment of the river conductance based on the riverbed slope.

Zone ID	Riverbed slope, %	Conductance, m^2/d/m
1	< 4	0.1
2	4-6	0.25
3	6-8	0.5
4	>8	0.75-1

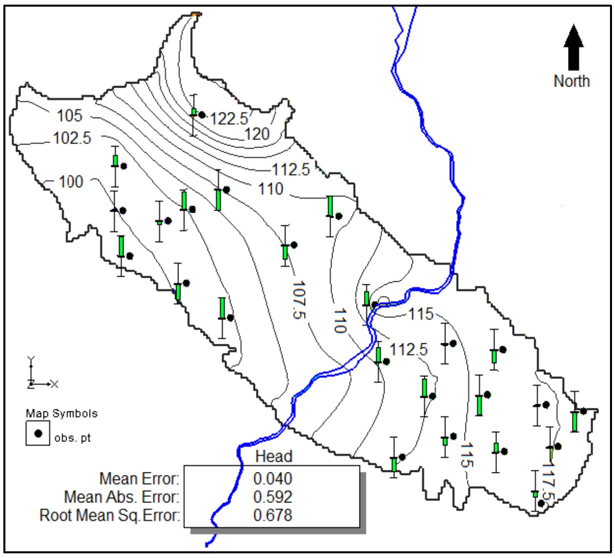

Fig. 6. Areal distribution of hydraulic heads and calibration targets at the end of calibration period.

3.2. The nature of river – groundwater interaction

Upon to table 2, the Dez river has a losing nature and recharges the aquifer consequently. In MODFLOW river package, the water exchange rate between a river and groundwater is controlled by the two factors: riverbed conductance and the hydraulic head difference between river and groundwater. In a losing river (Fig. 1b), these factors are formulated as below (Kresic. 1997).

$$Q_{river} = C_{river} \left(H_{river} - H_{aquifer} \right) \tag{7}$$

where, Q_{river} is the water exchange rate between river and aquifer [L^3/T], C_{river} is the riverbed conductance [L^2/T] and H_{river} and $H_{aquifer}$ are the river and groundwater hydraulic heads [L], respectively. If the groundwater head be located below the riverbed elevation, the Eq. 7 can be written as Eq. 8 (Kresic. 1997).

$$Q_{river} = C_{river} \left(H_{river} - R_{bottom} \right) \tag{8}$$

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where, R_{bottom} is the river bottom elevation [L]. In other words, the river water exchange rate doesn't depend to the variation of hydraulic head in the aquifer. Groundwater pumping, thus, has no effect on the rate of water exchange between river and aquifer. This situation is shown in Fig. 1c and 1d.

Table 2. Simulated volumetric budget for the period of 2013 Sept. to 2014 Sept.

In	Flow, m^3	Out	Flow, m^3
Storage	121144784	Storage	34287828
General head boundary	88729792	General head boundary	122432240
Rivers	12010451	Rivers	0.0
Wells	0.0	Wells	145700064
Recharge	80550560	Recharge	0.0
Total IN	302435584	Total OUT	302420128

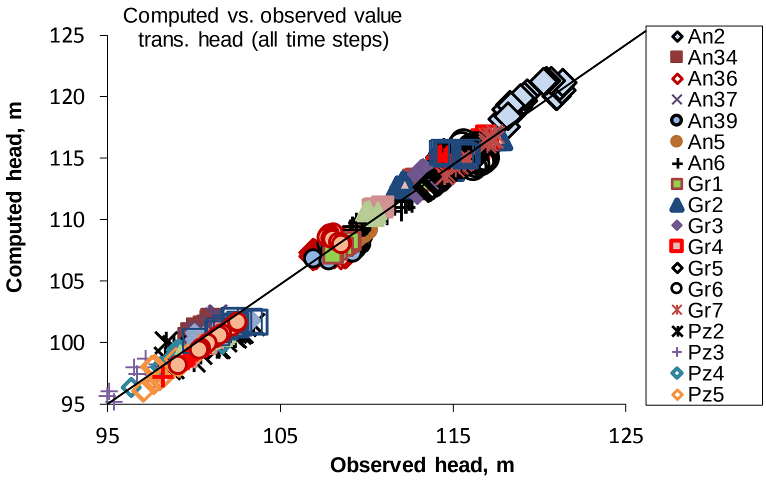

Fig. 7. Computed versus observed heads in the simulation period (2013 Sept. - 2015 Sept.).

To evaluate the variation of the Dez river infiltration to the aquifer under the groundwater extraction conditions, the pumping rate of the river adjacent wells were increased by 5, 10 and 20 percent. But, there was not seen any changes in the river infiltration rate to the aquifer. So, the modeling results show that the groundwater pumping from the river adjacent wells has no effect on the river- aquifer exchange rate. And the Dez river acts as a losing connected river (Fig. 1c). The groundwater potentiometric maps and the decreasing trend of the physicochemical parameters of groundwater in river adjacent wells (Chitsazan et al. 2015) also confirmed this finding.

3.3. Temporal and spatial variation of river–groundwater interaction

The river water stage and riverbed conductance are two main factors, as it previously mentioned, and control the river recharge to Dezful-Andimeshk aquifer. The river level fluctuations, thus, have a significant effect on the water exchange rate between the Dez river and groundwater.

The Dez river discharge is under influence of the water release from the Dez dam in the north of the study area. Also, the water release pattern of the Dez dam has a significant effect on the water exchange rates between river and groundwater, consequently. As shown in Fig. 8, the rate of water exchange between the river and groundwater has a good correlation with the water release pattern from the Dez dam. Also, the most water exchanges occur during the March to June (Fig. 8).

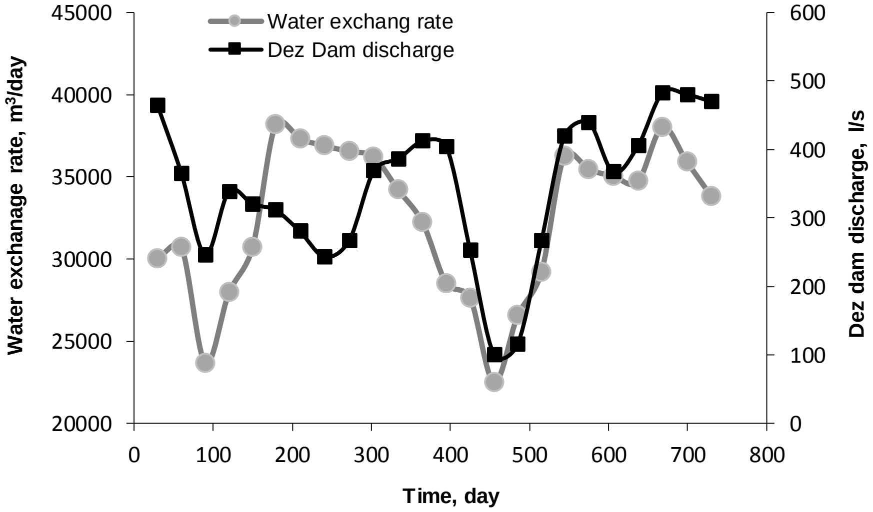

Fig. 8. Temporal variations of river recharge to aquifer in the simulation period.

To evaluate the spatial variation of river- aquifer interaction, the aquifer area around the Dez river was divided into seven zones (Fig. 9). The river-aquifer water exchange rates, then, were calculated using the MODFLOW zone budget package. Fig. 10 shows the volume of water exchange in different zones. As shown in Fig. 10, the most recharge from the river occurs in zone 3, 5 and 6. The riverbed sediments include coarser sediments, due to the higher slope of the river channel in these zones. The riverbed sediments in aforementioned zones consist of coarse gravel and pebble with some sand. Therefore, the water exchange between the river and groundwater occurs more easily compared to other regions in the river channel.

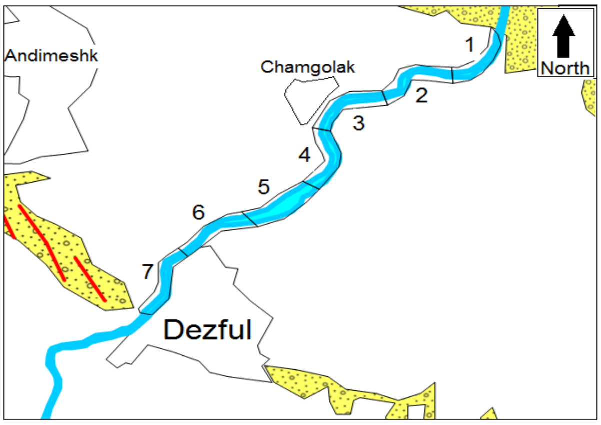

Fig. 9. The river zones for the water budget calculations.

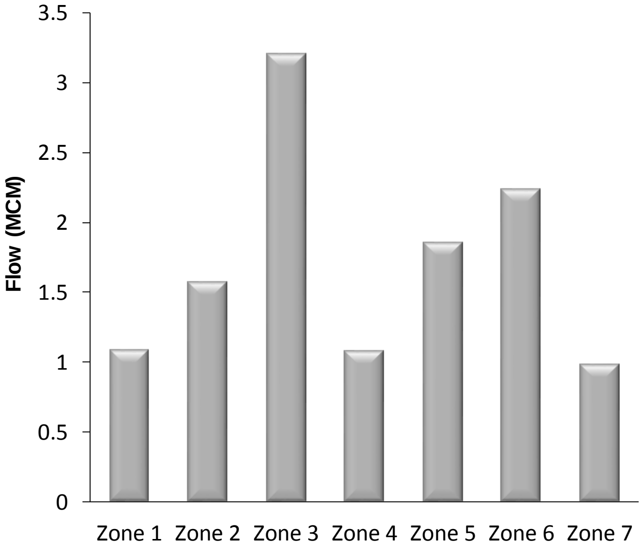

Fig. 10. Rate of river recharge in different zones.

3.4. Water table maps in river connected aquifers

In aquifers that are connected to rivers, sometimes the groundwater potentiometric maps cannot correctly show the nature of river- aquifer interaction. In the case of losing rivers, this situation is more significant. It is recognized that many factors are responsible for inability of water table contour pattern correctly showing the nature of river-groundwater interaction. High concentration of pumping wells, for example, with high pumping rates in the river adjacent location can alter the pattern of iso-potential lines (May and Binti Mazlan. 2013). So, the variation pattern of equipotential lines doesn’t properly show the river–groundwater interaction. In the study area, the drinking water supply wells of the Dezful city are located near the river in the north of the Dezful city. The previous studies showed that the Dez river has a losing nature. But due to the high pumping rate of drinking supply wells (about 10 MCM per year), the pattern of the potentiometric map does not show the losing status of the river in area around the drinking water supply wells (Fig. 11).

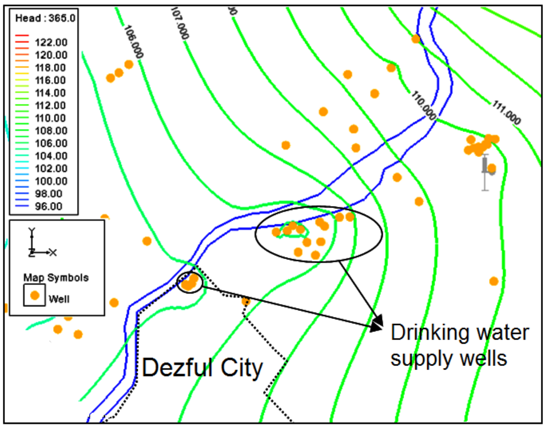

Fig. 11. The water table contours around the water supply wells of Dezful city.

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In this area, the rate of river recharge to the underlying aquifer (about 2.3 MCM per year) is much lesser than the rate of groundwater pumping by the water supply wells. So, the river recharge water cannot compensate the water table drawdown resulting from groundwater pumping.

4. Conclusions

In this study, the interaction between Dez river and groundwater was evaluated, using the numerical simulation of groundwater resource in the north part of the Dezful-Andimeshk district. This study was carried out in three steps. First of all, the required data for the construction of numerical model were prepared. These data include hydraulic head data, pumping rates of extraction wells, river characteristics, surface recharge rate and aquifer hydraulic conductivity and specific yield. The riverbed conductance values were assigned according to the topographic and sedimentological characteristics of the river channel. Due to these features, values ranging from 0.1 to 1 m^2/d/m were assumed for river conductance. The rate of surface recharge was calculated by the WetSpass model. This rate varies between 47.1 to 191.8 mm/year. And the areal distribution of hydraulic conductivity and specific yield were obtained according to pumping test results and the cluster analysis of water table data. The hydraulic conductivity and specific yield values ranging between 15 to 45 m/d and 0.15 to 0.18 respectively. In the second step, the groundwater flow was simulated, using the GMS interface. The groundwater system was simulated for the 2013 to 2015 period. In the third step, the calibrated model was used to evaluate the water exchanges between the Dez river and groundwater. The results show that the Dez river acts as a connected losing river. This river recharges the underlying groundwater body with a rate of 12 MCM during the 2013 to 2014. However, the river recharge rate is varying temporally and spatially. From the temporal point of view, the greatest water exchanges between the river and groundwater occurs during March to June. The water release pattern of the Dez dam also had a significant effect on the temporal variation of river- groundwater interaction. There is a good correlation between the water release pattern from the Dez dam and the rate of water exchange between the river and the aquifer. From the spatial point of view, the maximum water exchanges occur in areas near the Chamgolak town and Dezful city. The topographic characteristics of the Dez river channel in these locations make suitable zones for the river –groundwater interactions. The riverbed sediments near the chamgolak town and Dezful city include coarser sediments, due to the higher slope of the river channel. So, the river- aquifer water exchanges occur easier in aforementioned locations. Also, this study showed that sometimes the groundwater potentiometric maps are not correctly capable to show the nature of river- aquifer interaction, especially when there is a high concentration of extraction wells in river adjacent. In this situation, the infiltrated water by the river cannot compensate the drawdown resulting from the abstraction wells.

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