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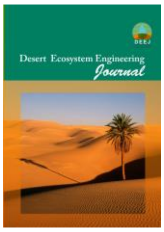

Hydrological Impacts of Large Reservoir Dam and Land Subsidence on Downstream Groundwater Resources using Mathematical Modeling

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Abstract

Spatial and temporal change of groundwater recharge is crucial for effective groundwater resources management especially in arid and semi-arid regions. Human activities such as reservoir construction commonly interrupt the balance of the subsurface system. At the end of the 20th century, about 45,000 large dams have been constructed in the world, mainly in the arid and semi-arid region. The main aim of this study was to investigate the interaction impacts of land subsidence and dam construction on Mosian aquifer located at the north-west of Iran. Groundwater mathematical model (MODFLOW), Geographic Information System (GIS), and climate model (LARS WG) were used for predict the impact of dam construction on groundwater balance of the study area. According to results, from 1991 to 2014, groundwater level declination and land subsidence at the downstream area of the dam were 11.22 and 0.45 meter respectively. Constructed dam has different effects on some components of water balance. River recharge decrease by 65 percent, whereas, recharge through return water increase by 50 percent. The results of the prediction indicate that groundwater level will decrease continually, as the annual groundwater declination will be 0.58m for the period of 2015 to 2030.The results also show that dam construction should decrease the trend of the groundwater declination. Predicted average of groundwater declination was 0.58 and 0.65 when simulation was implemented for dam and no dam condition respectively. The effect of land subsidence on groundwater declination was not noticeable compared to effects of the groundwater discharge.

Keywords: Land subsidence, Groundwater over-extraction, Large dam, Mathematical model, Groundwater declination.

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1. Introduction

At the end of the 20th century, about 45,000 large dams have been constructed in the world, mainly in the arid and semi-arid region (ICOLD, 2013). When human activities such as dam construction, associate with the climate change, a regional heterogeneity of water resources souled be occurred (Sccanlon et al. 2006). Understanding the effects of the dam construction on groundwater balance characteristics is crucial for water resources management. But, spatial and temporal variations of the inputs and outputs of the groundwater resources lead to uncertainties in predicting regional groundwater balance (De Vries and Simmers 2002). Due to their size and function, reservoirs should positively or negatively affect the local climate, hydrology, and economy of the related area. The effect of the reservoir on individual flood flows depends on the both of the storage capacity of the dam and the way that dam is operated. A consequence of the dam construction is reduction of the floodplain inundation; consequently, the groundwater recharge should decrease (Koichi Sakakibara, 2015).

Dam construction should also changes the upstream and downstream flows of the rivers. At the upstream, river change may occur in order to increase the capacity of the reservoir. This measure may affect the surface and the groundwater systems. Groundwater levels may decrease in the areas with diverted rivers and increase in the downstream or in the areas close to reservoirs (Cause, 2001).

In addition to altering the flow regime of the rivers, dams should affect the total volume of the surface runoff. Impact of dam on surface and subsurface water was studied from different perspectives including; the impacts on flood e.g. Sait Tahmicioglu et. al. (2007), geomorphic impacts e.g. Skalak et al. (2013), the impacts on the hydrological regime of the river e.g. Ma et al. (2012), the impacts on the amount of the sediment and sediment yield e.g. Yuan et al. (2012); Overeem et al. (2013); Nelson et al. (2013), the effects on the temperature of the river e.g. Risley et al. (2010), environmental impacts e.g. Aqeel et al. (2014), and the impacts on water quality e.g. Kamel &Almula, (2016). The effect of the Badush dam on groundwater level was predicted using MODFLOW (Aqeel et al. 2014). According to results of this study, dam construction has a positive impact on groundwater level. the storage in the aquifer (as the storage increases). Kamel and Almula (2016) indicate that sand storage dams should improve water quality.

Aquifer capacity and groundwater flow velocity should determine by the porosity of the subsurface material. Groundwater over-extraction should cause some degree of subsidence as aquifer materials adjust to new stresses. The result of study by Budhu & Adiyaman, 2010showed that land subsidence can cause damage to building and infrastructure of the aquifers. Many researchers have done work on subsidence as a result of excessive ground water withdrawal, e.g. Bhattacharya (2008), Sahu and Sikdar (2011) etc. They indicate that decline of water table due to excessive ground water withdrawal accelerates the process of land subsidence.

Separate studies have been done on the effects of dams, over- exploitation of groundwater and aquifer subsidence. This study focused specifically on the quantitative effects of dam construction and land subsidence on the downstream aquifer using MOFLOW. In order to quantify the interaction impacts of the dam construction and land subsidence, four models were examined to simulate the ground water flow based on the four following scenarios: Existence of dam and existence of land subsidence (scenario I); Existence of dam without land subsidence (scenario II); Existence of land subsidence without dam (scenario III); Without dam and land subsidence (scenario IV)

2. Material and methods

2.1 Study area

Doiraj watershed (DW) with an area of 3500 sq. Km located at the southern part of the Ilam province in the North-west of Iran (Figure.1). This watershed consists of three geomorphologic units (mountainous, hilly and plain). Doiraj dam catchment with an area of 1200 sq Km consists of 35 sub-basins constitute. The Doiraj dam (with a total capacity of 191 Mm^3 at full reservoir level; 60m) is an earthen dam that constructed across the Doraj River. Dam construction was started in 2008 and completed in 2012. The Mosian aquifer located at the alluvial Mosian plain, downstream of the Doiraj dam. The groundwater characteristics of the studied area have been mapped regionally based on the interpretation of 23 piezometer data, 4 exploration wells data, geological data and hydrological information. The majority land-use of the studied area is rangeland (81.4%). Agri-land accounts for 18.3%, while only 0.02% is residential areas.

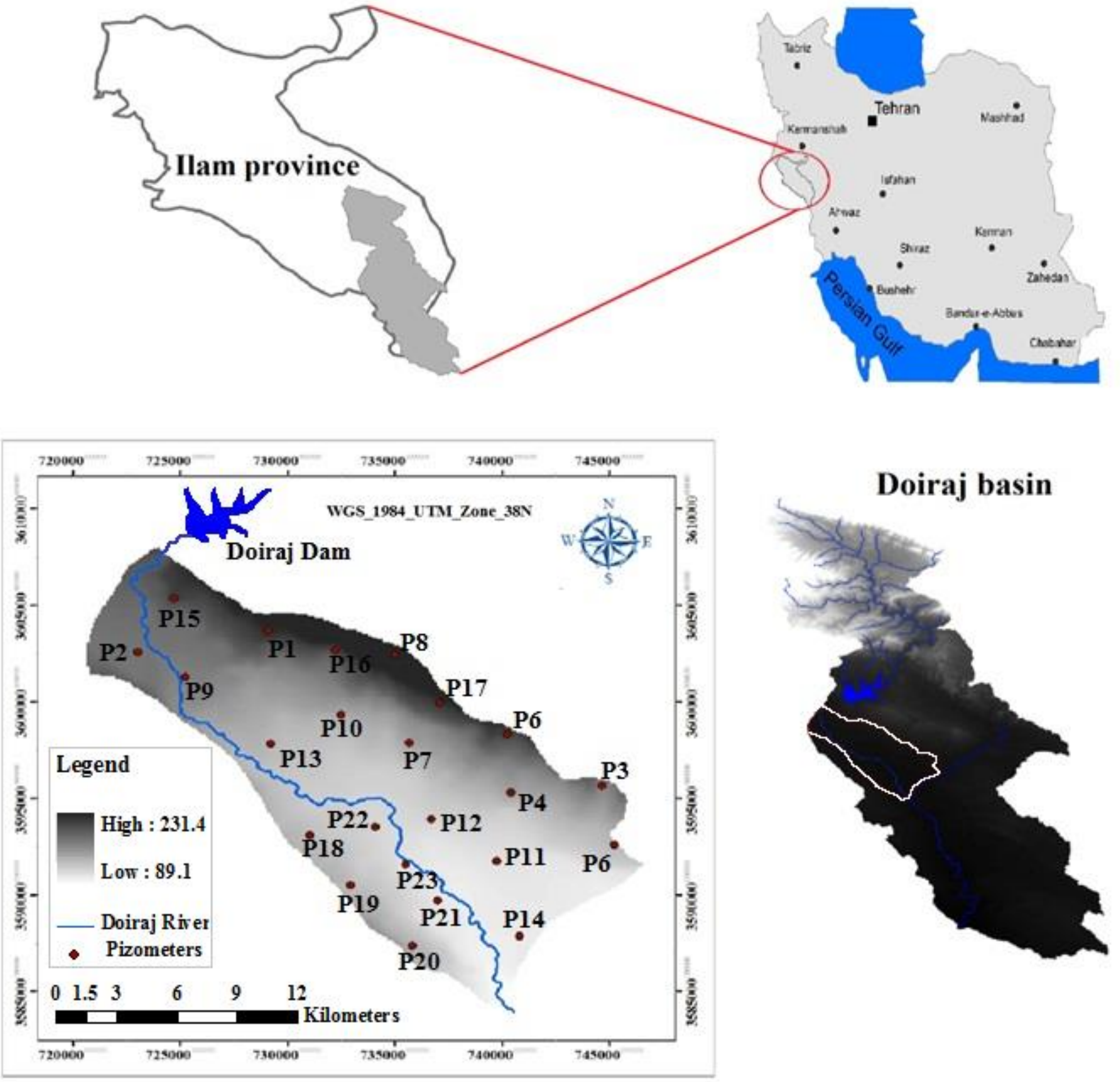

Fig 1: Location of the study area and piezometric wells in Ilam province, Iran

2.2 Methodology

This study was conducted in four main parts:

In the first stage, the hydraulic head drop in the study area was calculated using measured groundwater level data. Then land subsidence was estimated as a result of the groundwater over-extraction.

In the second stage, the numerical model of the aquifer (1990-2014) was generated using MODFLOW. The groundwater characteristics of the study area have been also mapped regionally based on the interpretation of 23 piezometer wells data using geology and hydrology information of the study area.

In the third stage, the current and future condition of the aquifer was simulated based on the groundwater extraction rate, effects of Doiraj dam on river discharge, and irrigation water.

Finally, the hydraulic head of the aquifer was predicted for 2015-2030 using calibrated model.

2.2.1 Ground water flow model

According to Scanlon et al. (2002), as groundwater is essentially a hidden resource, studies on groundwater under both natural and artificial boundary conditions require modeling techniques. In this study, a regional-scale Mathematical Groundwater Model (MODFLOW) was developed in the Mosian region to simulate aquifer conditions, to estimate aquifer parameters, and to predict groundwater condition before and after construction of the Dorja dam, as well as under land subsidence condition.

MODFLOW is a three-dimensional finite-difference groundwater flow model that was first published by the USGS in 1984 (Harbaugh et al. 2000). For groundwater flow simulation, MODFLOW uses continuity equation (Eq.1), Darcy's Law(Eq.2) and Finite Difference Model (Eq.3).

$$\sum Q_i = SS^{\Delta h} - \Delta V \qquad \text{(eq.1)}$$

Where, Qi is flow rate into the cell ($L^3.T^{-1}$), SS is a term equivalent to specific storage ($1.L^{-1}$), ΔV is change in volume of the cell (L^3), and Δh is change in head over a time interval (L).

$$Q = -kA\frac{dh}{dl} \qquad \text{(Eq.2)}$$

Where,
Q is flow rate ($L^3.T^{-1}$), K is hydraulic conductivity ($L.T^{-1}$)), A is area (L^2), and
dh/dl is hydraulic gradient ($L.L^{-1}$).

$$\frac{\partial}{\partial x}\left(-k_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(-k_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(-k_z\frac{\partial h}{\partial z}\right) = S_S\frac{\partial h}{\partial z} \pm q_s \qquad \text{(Eq.3)}$$

Where, Kx, Ky, Kz are Hydraulic conductivity along x, y and z, h is total hydraulic head, qs is sources and sinks, Ss is specific storage and t is time.

In this method, an aquifer system is divided into rectangular blocks by a grid. The grid of blocks is structured by columns, rows, and layers, and each block is commonly called a "cell." In this study, 61596 square grid cells (261 columns and 236 rows) with 100 m dimension within the boundary of Mosian district were created. Cells located inside of the aquifer boundary were showed by type 1 in which rise or drawdown may occur. Cells located outside of the district boundary were indicated by 0 types, signifying no flow cells. For each cell there are several inputs including aquifer characteristics and information relating to the wells, rivers, and other inflow and outflow features of the cell.

In this study, the year of 1991 was selected for modeling of Mosian aquifer in the steady state condition. Period 1991-2014 determined as the unsteady condition. This period was divided to 46 time steps with 6 month length. Period 2015-2030 selected as the forecast period.

Necessary data was obtained from various regional and local government offices (geographic maps from the regional water organization (RWO), annual rainfall data from the meteorological organization, water level in the aquifer and groundwater data from the regional water organization, Irrigation data from the previous studies and groundwater data from the regional water organization. Land use maps were obtained from the satellite images (LandSat). Monthly Groundwater level measured in 23 borehole wells from 1991 to 2014 was used.

2.2.2 Impact of Dorja dam on Downstream Groundwater Resources

For study the hydrological impact of Dorja dam on groundwater characteristics, after model calibration and validation, aquifer parameters was simulated for the condition before and after construction of the Dorja dam.

2.2.3 Land subsidence rate

Groundwater over extraction lead to land subsidence, consequently, hydrological behavior of the aquifer should change. A variety of techniques have been improved to estimate land subsidence. Global Position Systems (GPS), satellite measurement, manually level measurement, Persistent Scatter Interferometry (PSI) and empirical equations are some of the usual methods for estimating of the land subsidence.

There is no comprehensive land subsidence monitoring program in Mosian plain. Relation between land subsidence and groundwater level was studied in the adjacent aquifer (Mehran Plain) that is similar to Mosian in terms of geology, materials and formations, aquifer type, climatic conditions, agricultural conditions, cropping pattern and groundwater exploitation (Zamani et al. 2016). A regression equation was presented between the amount of water table declination and land subsidence in the Mehran plain. During field surveys, the evidence and the effects of the land subsidence in the studied plain was evaluated and this equation was adapted for the study aquifer (Eq.4).

$$Y = 0.9771X + 4.6126 \qquad R^2 = 0.74 \qquad \text{(Eq.4)}$$

Where, Y = land subsidence (cm), X = amount of groundwater drop (m).

2.2.4 Interaction impacts of dam construction and land subsidence during 2015-2030

In order to quantify the interaction impacts of the dam construction and land subsidence, four models were obtained to simulate the ground water flow based on four following scenarios:

1. Existence of dam and existence of land subsidence (scenario I)
2. Existence of dam without land subsidence (scenario II)
3. Existence of land subsidence without dam (scenario III)
4. Without dam and land subsidence (scenario IV)

First scenario is real conditions of the aquifer, but in order to estimate the impacts of dam and land subsidence, the model was run all scenarios, and unit hydrographs of the plain were compared.

For each scenario, monthly groundwater level was predicted for 2015-2030. Information layers for 32 time period (6 month length for each time period) were entered to the MODFLOW model, and monthly water level was predicted.

The recharge layer via precipitation was prepared using predicted rainfall by LARS Weather Generator. For river package (), Average data of the last five years before dam construction was entered to the MODFLOW as the river data for the condition of nonexistence of dam. While, fixed amounts of the annual river discharge after dam construction was used to simulate the condition of the existence of dam. For nonexistence of dam, the recharge via return flow layer was simulated based on the water consumption in the latest year before construction of the dam. The volume of transferred water via irrigation network located in the dam downstream was used to indicate the state of the existence of the dam.

3. Results

3.1 Groundwater modeling before construction of dam (1991-2014).

According to results, for 23 observation boreholes well, determination coefficient (R^2) for groundwater levels was 0.96 during the calibration period (1991-2006) and 0.93 during the validation period (2007-2014). These results show the accuracy of the MODFLOW model as a management tool to scrutiny of difference suggestions, policies and scenarios.

Impact of dam on recharge and discharge components via river leakage and irrigation return flow was also estimated. Annual flows of the Doiraj river (1991-2012) were used to investigated the impacts of dam on river flows (Figure 2). According to results, before dam construction, river discharge varied between 0.9 m^3/sec in the dry season to 650 m3/s in the wet seasons. After the construction of the dam, the wet season flows have decreased to 0.98 m^3/s.

Long-term average discharge of Doiraj river was 6.14m^3/s.To evaluate the fluctuations of the river flow, river hydrographs were extracted over the period of 1986 to 2014 (Figure 2). According to results, the annual flow of the Dorja river has fluctuated before dam construction, but Doiraj river flow controlled via dam construction, consequently, river flow reached to the steady state. It is expected that any changes in the river flow should affect the water balance of the related aquifer.

The impacts of the dam construction on the river flow and groundwater recharge and discharge via river was quantified. Based on the results, in 1991 (before construction of the dam) annual aquifer recharge and drainage via Doiraj river was about 8.5 and 3 MCM respectively. Estimated annual groundwater recharge via Dorja river (1991-2012) was about 10.5 MCM. Groundwater discharge via Dorja river decreased via dam construction by about 7 MCM and keeps it almost constant (about 3 MCM annually) (Table 1).

The groundwater recharge via irrigation return flow increased from 7.1 MCM in 1991 to 13.6 MCM in 2012, whereas groundwater discharge via pumping increased from 18MCM in 1991 to more than 60MCM in 2012. In general, the recharge by the return flow increased to 20 MCM (about 50% of growth) due to transferred of water from the Doiraj dam for irrigation (Table 2).

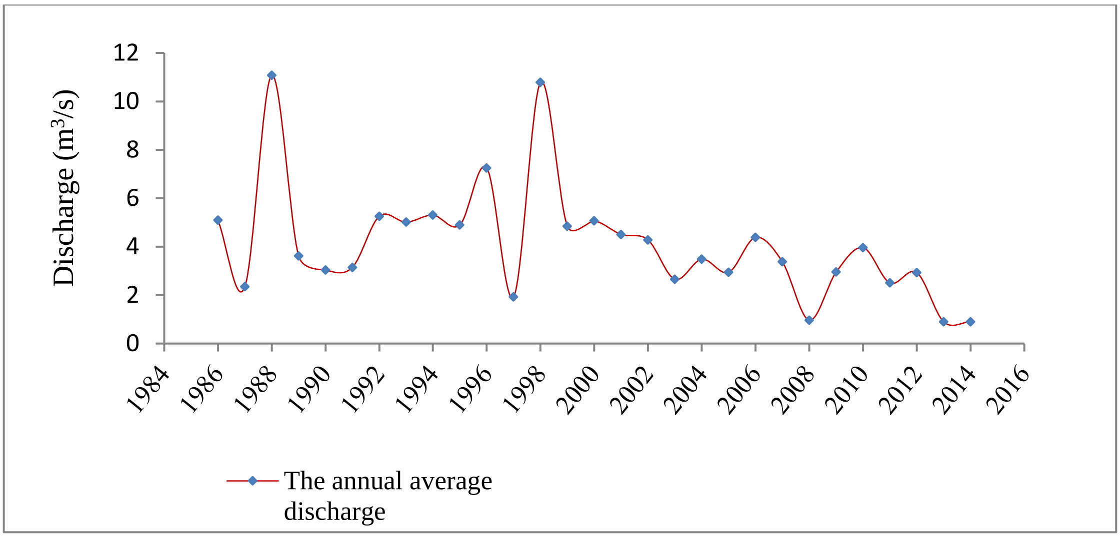

Fig 2: Annual hydrograph of Doiraj river (1986 -2014)

Table 1: The groundwater recharge and discharge via Doiraj river (estimated using MODFLOW)

Row	Year	River recharge (m^3)	River discharge (m^3)	Row	Year	River Recharge (m^3)	River discharge (m^3)
1	1991	8595969	3048113	13	2003	7245158	1661237
2	1992	14349909	2932540	14	2004	9513889	1520664
3	1993	13691880	2816967	15	2005	8038204	1380091
4	1994	14487735	2701394	16	2006	11975563	1239518
5	1995	13381297	2585821	17	2007	9215047	1098945
6	1996	17813342	2470248	18	2008	2630861	958372
7	1997	5256166	2354675	19	2009	7959788	817799
8	1998	19465660	2239102	20	2010	8187109	677226
9	1999	13229512	2123529	21	2011	7832467	536653
10	2000	13838474	2007956	22	2012	7705146	396080
11	2001	12309619	1892383	23	2013	3058918	255507
12	2002	11688590	1776810	24	2014	2958918	114934

Table 2: The groundwater recharge via return flow (estimated using MODFLOW)

year	Agricultural lands (ha)	Return flow (MCM)	Return flow into aquifer (mm)	Recharge computation factor
1991	4766	7.1	27.1	0.152
1993	5256	7.8	30.1	0.15
1995	7349	8.4	32.3	0.148
1997	10925	11.8	45.4	0.146
1999	12431	12.8	49.4	0.144
2001	12629	13.7	52.9	0.142
2003	12829	14	54.1	0.14
2005	13029	14.1	54.5	0.138
2007	13229	14.1	54.4	0.136
2009	13429	13.9	53.7	0.134
2011	13639	13.7	52.9	0.132
2013	13876	13.6	52.2	0.13
2015	13876	13.4	51.4	0.128
2017	13876	20.4	78.7	0.126

3.2 Groundwater fluctuations and land Subsidence

The long term trend (1991-2014) of the groundwater level situation was analyzed to indicate the impacts of groundwater fluctuations and land Subsidence**.** Groundwater fluctuations in the Mosian aquifer is shown in figure (3) and groundwater observation time series of 23 observation wells in the studied aquifer are shown in figure (4). According to results, groundwater table decreased continually since 1991(figure 3), but groundwater declination was vary in different parts of the studied aquifer (Figure 4). Maximum declination was occurred in the central parts of the studied aquifer (wells number P-04, P-07 and P-10 in figure 1).

From 1991 to 2012, estimated land subsidence was between 5 and 36 cm in the different parts of the studied area (Figure 5). Most land subsidence occurred in the central part of the studied area, where maximum groundwater declination was happened.

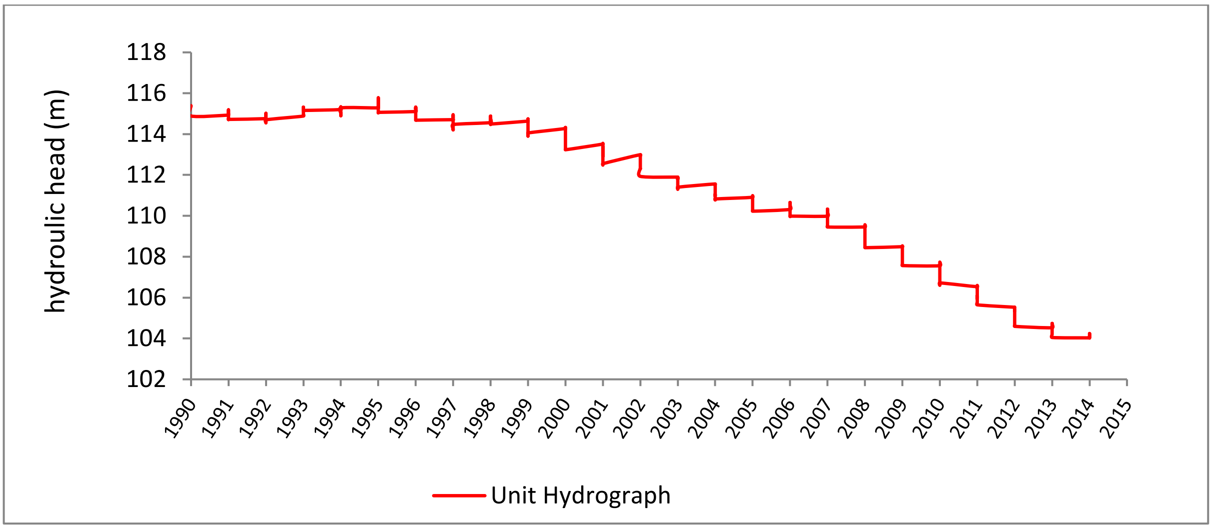

Fig 3: The monthly unit hydrograph of the Mosian aquifer (1991-2014)

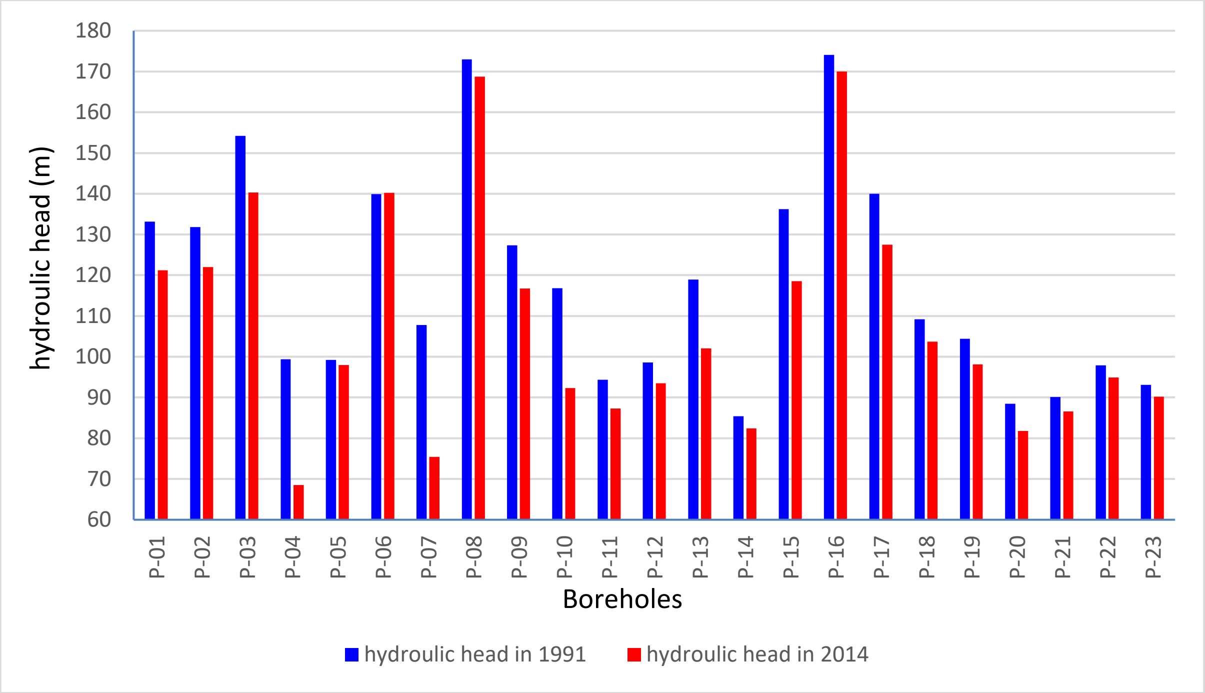

Fig 4: The Hydroulic head in observed wells in the Mosian aquifer (1991-2014)

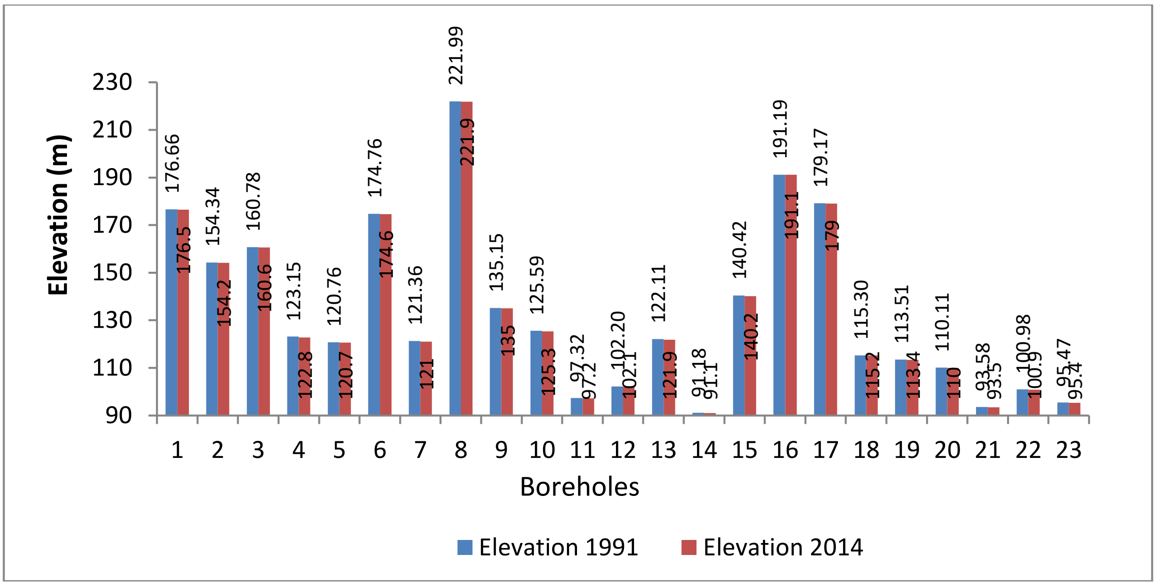

Fig 5: The amount of the estimated land subsidence in each of the observed wells

Based on the different scenarios, unit hydrographs of the study plain were extracted for the prediction period (figure 6). For the first scenario (considering the current utilization of the aquifer), declination of the aquifer level will be 9.37 m in 2030. Also aquifer levels will dropped at a more accelerated rate based on the scenario II (9,38 m in 2030),but the impact of land subsidence on water level fluctuations was negligible during the prediction period (only 1 cm) .Under scenario III and IV, downfall level of the aquifer will be 10.33 and 10.32 m in 2030 compared to 2014. So, impact of the land subsidence is similar in the both states of the existence and nonexistence of the dam. . According to results, Doiraj dam should prevent from the further water level declination (about 1 m in 2030).

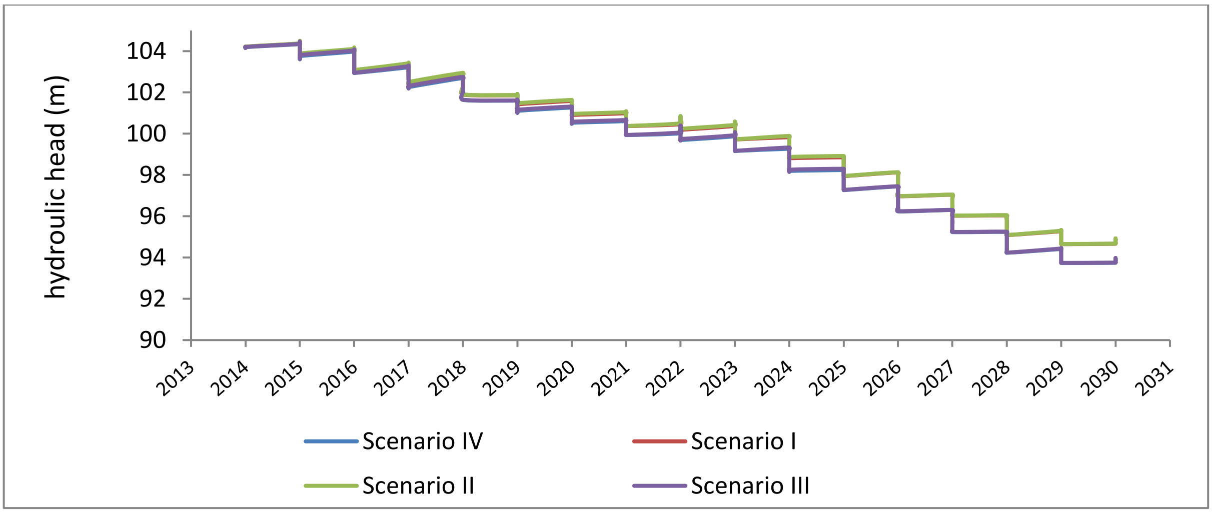

Fig 6: The monthly unit hydrograph of Mosian aquifer for four suggested scenarios (predicted using MODFLOW) during 2014-2030

4. Conclusion

In this study, the effect of dam construction on the downstream aquifer level was simulated under conditions of over-exploitation of groundwater and the existence or nonexistence of land subsidence. The results of this study indicate the accuracy of the MODFLOW for simulation of the groundwater flow in a semi- arid area. The performance of MODFLOW model to simulating of the groundwater flow was also reported in other studies e.g. Al-Hassoun et al. (2011); Cho et al. (2008); Zhang & Hiscock, (2010); Yaoti et al. (2008); Riasat et al. (2012).

According to results of this study, construction of dam decreased river flows of the downstream, consequently groundwater recharge via river flow decreased (before dam construction in 1991, groundwater recharge via river flow was 8.5 MCM, while it decreased to 3 MCM after dam construction in 2014.

Estimated land subsidence in the Mosian aquifer was about 5 to 36 cm during 16 years, but no significant effects on groundwater level was estimated for land subsidence. Land subsidence due to over-extraction of groundwater was reported via several researchers around the world e.g. Phien et al. (2006); Larson et al. (2001). Also dam construction decreased groundwater recharge by the river, but totally, dam construction decreased groundwater declination of the study aquifer. Groundwater extraction should decrease from 59MCM to 27MCM to achieve the aim of sustainability of the aquifer. Change in crop pattern and irrigation systems should lead to increasing of the water efficiency and consequently, groundwater extraction should decrease.

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