



Research Article

Underground Dam Locating for Sustainable Groundwater Management Using Numerical Simulation

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Abstract

The main purpose of this study is to investigate the groundwater resources of Khatoon-Abad plain in Iran to achieve a sustainable management strategy. Increasing the groundwater exploitation, especially since 1980, has caused a decrease in the groundwater level. In this study, the fluctuation of water table in the central parts of the aquifer was simulated using PMWIN software. The research process included the flow model simulation, calibration, verification and implementation of underground dam. Hydraulic conductivity, specific yield and surface recharge were considered as calibration parameters. The results of finite difference simulation showed that the range of hydraulic conductivity varied from 1.5 to 11 m/day, which indicates loamy soil in most areas of the plain with good transmissivity. Moreover, the specific yield changed from 0.008 to 0.06, which showed more values in the middle parts of the plain. Two positions were considered to evaluate the effect of the underground dam, which was selected according to the availability and volume of stored water and the material of the porous environment of the reservoir. The height of water rise and the effective radius of the dam in these conditions were estimated to be about 5.8 m and 3.5 km, respectively. The first point downstream of the dam after five years was faced with a 4.9 m withdraw in water table.

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Keywords: Hydraulic conductivity; Khatoon-Abad aquifer; Simulation; Specific yield

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1. Introduction

Water demands with growing population and consumption have been increased and the groundwater reservoirs are steadily reduced in arid and semi-arid areas. Therefore, the runoff and rainfall during the winter should be collected and infiltrated into the permeable covering layer in these regions where droughts occur in succession (Lalehzari et al. 2020). The gathered water can be used during summer for irrigation areas (Fakharinia et al. 2012; Tabatabaei et al. 2010; Lalehzari et al. 2020). Underground dam is one of the main strategies which can be considered as a managerial and practical policy in different countries, especially in semi-arid regions (Lalehzari and Tabatabaei, 2015). The technology of

underground structures have been confirmed as an efficient plan for conserving the available groundwater and sustainable approach for agricultural water allocation (Lalehzari and Kerachian 2020, 2021). Underground dam structure is considered as a viable option for groundwater management. One of the underground dam merits is that the surface area can be used in the same way before and after the construction of the underground dam. This technology has been implemented to control the sedimentation, industrial water supplement and increasing the water availability in agricultural lands. Concrete material is used for the underground barrier to intercept the natural groundwater flow and provide storage for water underground is a common practice in many parts of the world, notably in Africa, India, Japan, Brazil, and

Saudi Arabia (Milanovic 2004; Tayari and Shamsaei 2006; Lalehzari et al. 2015).

Several studies have been carried out to evaluate underground dam (Ishida et al. 2013; Lalehzari and Tabatabaei, 2015), locating the suitable construction site (Gobashy and Al-Garni 2008) and the effect of underground structure on groundwater quality (Onder and Yilmaz 2005; Ishida et al. 2011). Furthermore, similar hydraulic structures have been implemented in different regions of Iran.

The main priorities for locating the underground dam construction are suggested in the previous studies such as: 1) appropriate geotechnical condition, 2) maximum possibility of backwater level, 3) economical storage capacity due to the construction costs; 4) suitable porous media and water quality (Milanovic 1988; Raju et al. 2006; Lalehzari et al. 2015). Assessment of the potential areas for underground dam construction was investigated in the recent years by applying the geographic information system (GIS), analytic hierarchy process (AHP), numerical simulation (Dai 2016; Kordi et al. 2016; Baharvand et al. 2020).

Tayari and Shamsaei (2006) simulated a finite difference numerical model based on the physical structure using Modflow for addressing the reservoir capacity of underground dam. The results showed that the effective parameters on water level were elevation, hydraulic conductance, effective porosity, discharge, initial water table, thickness of the saturated layer, and the longitudinal slope of bed layer. Lalehzari et al. (2015) developed a numerical model for estimating the groundwater level raise and nitrate concentration after the dam construction in Shahrekord aquifer, Iran. The simulated model was applicable to long-term prediction of changes in quantity and quality characteristics of the underground reservoir. Baharvand et al. (2020) reported that the river density, slope, water quality, lithology, land use, the thickness of sediments, and wells had the most important role in locating underground dam construction in Roomeshgan area. The results of several field studies and surveys show that more than three percent of the area is in a very suitable area and six locations were introduced as very suitable locations for underground dam construction.

The purpose of simulating the quantitative model of the aquifer in the first stage is to identify the hydrogeological status of the aquifer, then to check the accuracy and reliability of hydraulic parameters, statistics and laboratory and field information of the region. The effects of construction of underground structures such as underground dam projects on groundwater flow could be investigated. Therefore, in this study, a modeling framework was developed to estimate changes in the spatial distribution of groundwater level in Khatoon-Abad aquifer, Iran. The water table curve before and after the

construction of underground dam are predicted using calibration of Modflow (Harbaugh and McDonald 1988).

2. Materials and methods

2.1. Study area

Khatoon-Abad plain is located at 25° 55'E and 30° 01'N in Kerman province, Iran (Fig.1). Climatologically, the area experiences an arid climate, with average annual rainfall and temperature being 40.1 °C and 161 mm, respectively. Geologically, Khatoon-Abad occurs on the western margin of the Central Iranian Volcano-Plutonic Belt which hosts skarn and porphyry Cu-Mo mineralization such as Sarcheshmeh, Sungun, and Miduk deposits (Berberian and King 1981; Forghani et al. 2019; Nematollahi et al. 2020). The water budget parameters for the study year (October 2019 - September 2020) were summarized in Table 1. In this table, the components of water supplement and water allocation of the Khatoon-Abad aquifer have been presented. Storage changes in an alluvial aquifer are the sum of inputs minus the sum of outputs, which can be positive or negative. According to the groundwater balance of the Khatoon-Abad plain alluvial aquifer, the total annual inflow is 48.03 million cubic meters (MCM) and the total annual discharge amount is 50.18 MCM. Therefore, storage changes of Khatoon-Abad plain was -2.15 MCM. Considering the plain area of 329 km², the average drop of groundwater level by 0.007 m and storage coefficient of 4%.

2.2. Conceptual model

Conceptual modeling is the first step of simulation which describes the quality of the physical and hydrogeological framework of the aquifer. In a conceptual model, the hydrogeological factors are determined qualitatively and schematically and the shape of the aquifer is physically determined. The conceptual model is the basis of the mathematical model and is based on the principle information of field data and hydrogeological interpretation. Topography of surface and bedrock elevation, determination of stress periods and time steps, location of observation wells, definition of initial and boundary conditions and selecting the initial values of the aquifer parameters are the main modeling steps. In this model, geophysical studies were used to prepare the bedrock.

Modflow software as a three-dimensional groundwater model was implemented to simulate the water table fluctuation. Cells in Modflow are divided into two types that are used to describe grid boundaries. Inactive cells (no-flow) and cells with variable hydraulic head. For aquifer gridding, the aquifer map was first converted to bmp format and entered in the model field.

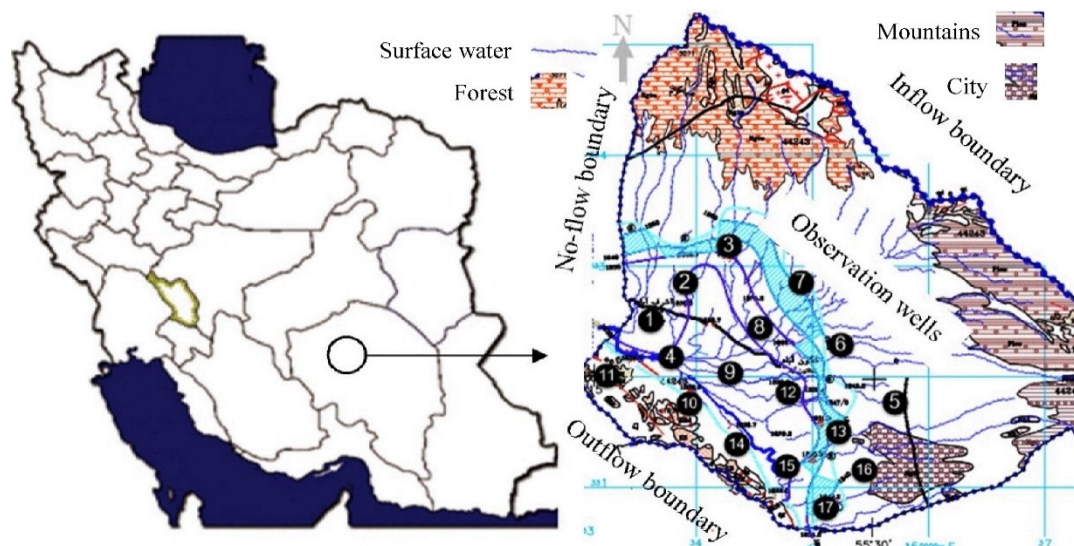


Figure 1. Khatoon-Abad plain in Kerman province, Iran

Table 1. Groundwater budget and surface water in Khatoon-Abad plain

Sources	Well	Spring	Qanat	Groundwater	Surface water	Total
Number	-	111	20	3	-	134
Depletion	MCM	41.09	5.24	2.85	50.18	3.87
						53.25

A grid with cells measuring 500 x 500 m was drawn to cover the length and width of the aquifer. Fig. 1 shows the main boundaries of the model. The Khatoon-Abad aquifer is an unconfined layer with 1343 km² area and elevation of 1840 m from sea level. Hydraulic boundaries were about 30% of the total boundaries of the region. This area has two underground inflow in the northeast and south and an outflow boundary in the western part of plain. Surface water in the study period was insignificant and had no effect on increasing or decreasing groundwater level. Furthermore, because of the water table depth in the whole plain was more than enough to be able to move capillaries for evaporation, the evapotranspiration component in groundwater budget equation could be eliminated. The effective porosity and the ratio of vertical to horizontal hydraulic conductivity are estimated at 24% and 0.4, respectively, according to pumping experiments.

2.3. Numerical simulation

Simulation was carried out based on the steady and unsteady states. Under steady state conditions, the entire study period is assumed to be a time step, and the input parameters to the model will not change until the end of the simulation. But unsteady state is more compatible with natural condition and also calculate more results. Modeling of Khatoon-Abad aquifer from October 2012 to August 2019 was divided into monthly stress periods. The mentioned time divisions were applied to all observation wells, exploitation, boundary condition (inputs, outputs, rainfall) and existing stresses. The model was calibrated for hydraulic conductivity, specific yield, general head boundaries and surface recharge coefficients. Hydraulic

conductivity was calibrated at steady state and other parameters were calibrated at steady state. The Recharge package is used to consider the spatial distribution of surface recharge in the area. Recharge due to rainfall and recharge due to return water of wells are the most important sources of positive parameters of water budget equation. The percentage of the precipitation infiltrated into the ground is obtained considering the deep percolation rate, land slope, and soil texture.

2.4. Simulating the underground dam

Underground dam is one of the hydraulic structures that has been recently studied in the sustainable management of aquifers (Ishida et al. 2013; Lalehzari et al. 2015). This structure should be simulated before than construction stage to evaluate its effects on the quantity and quality of the groundwater flow in aquifer. The special characteristics of an area that must be met to evaluate the managerial scenarios are: hydraulic conductivity, transmissivity, alluvial thickness, availability of the dam reservoir, riverbed, and construction materials. Two locations can be considered according to the above priorities and the direction of flow in Khatoon-Abad plain, which is indicated in Fig. 2.

3. Results and discussion

3.1. Calibration and verification

The comparison between observed and calculated groundwater levels in observation points for calibration and verification were presented in Fig. 3. Furthermore, the

evaluation indicators of root mean square error (RMSE) and coefficient of residual mass (CRM) were summarized in Table 2. As shown in Fig. 4 and Table 2, the accuracy of the simulated framework could be confirmed by RMSE 2.3 m with an overestimation especially in the verification periods (CRM=0.00031). The focus of the dots on the left side of the graph indicates an overestimation or a positive residual mass factor. The evaluation of calibration and validation results for different simulation periods showed that the highest and lowest accuracy belong to stress

periods 2 and 14, respectively, with a time interval of 180 and 1278 days from the beginning of the study time. Among all periods, stress periods of 1, 8 and 12 were negative residual mass coefficient and showed underestimation of results. The accuracy of the simulation according to the indicators is acceptable and approved. Furthermore, the groundwater level variations in the locations indicated in Fig. 2 (UD1 and UD2) were illustrated in Fig. 4.

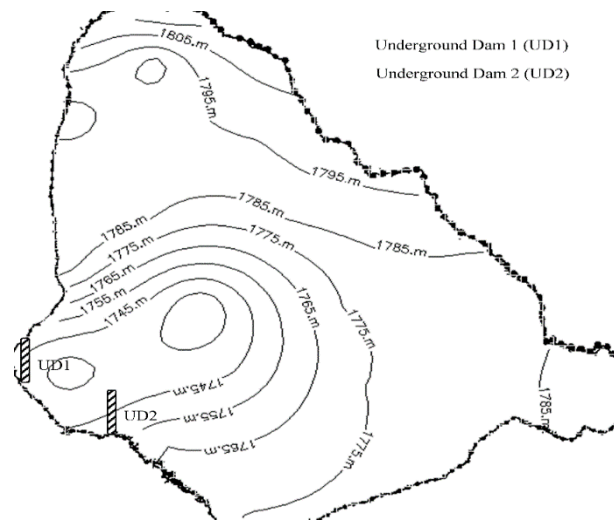


Figure 2. Locations of proposed underground dams for Khatoon-Abad aquifer

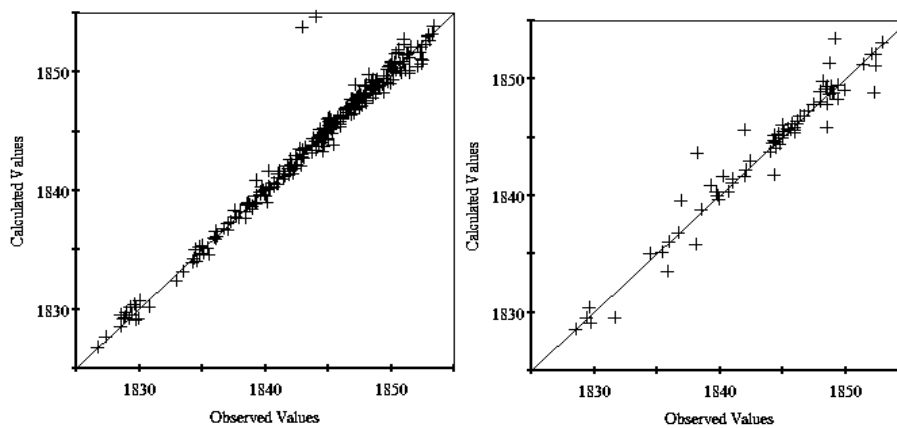


Figure 3. Calibration (left) and verification (right) of groundwater flow model

Table 2. Error indicators for different stress periods

Stress periods	Time day	RMSE m	CRM×10 ⁶ -	Stress periods	Time day	RMSE m	CRM×10 ⁶ -
1	90	0.35	-27.5	11	1005	0.78	64.9
2	180	0.30	14.1	12	1098	0.75	-50.6
3	273	0.71	315.4	13	1188	0.83	53.7
4	366	0.33	29.9	14	1278	3.30	852.0
5	456	0.47	20.1	15	1371	2.76	579.5
6	546	0.65	227.5	16	1464	2.72	548.9
7	639	0.67	17.8	17	1554	1.45	341.1
8	732	0.72	-112.4	18	1644	0.76	135.3
9	822	0.76	273.7	19	1737	2.34	464.9
10	912	0.94	188.1	20	1830	3.10	684.7

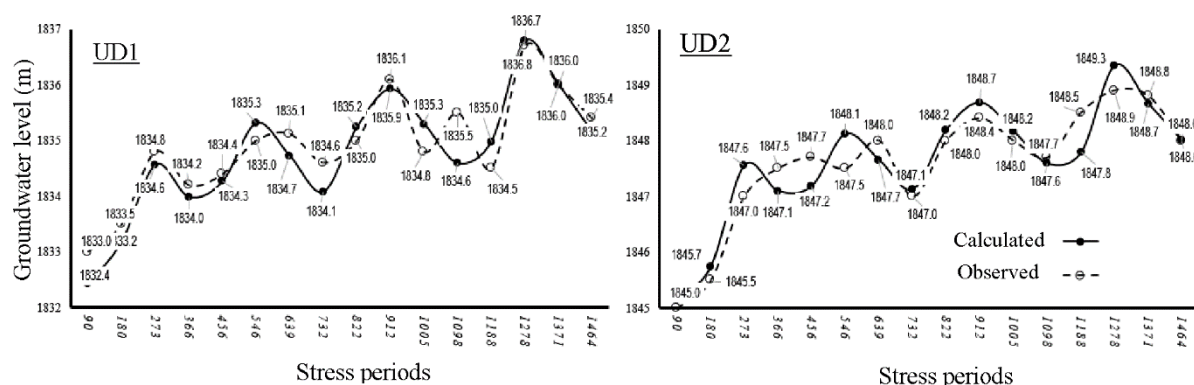


Figure 4. Comparison between calculated and observed water table in proposed locations of underground dams

Table 3. The range of calibrated parameters in different stress periods

Parameters		Minimum		Maximum		
		values	regions	values	regions	
Hydraulic conductivity	m/day	1.51	East boundaries	11.2	Center	
Specific yield	-	0.0079	East boundaries	0.063	Center	
Recharge	%	0	Urban	28	Agricultural lands	
GHB	Hydraulic conductance	m ² /day	1.8	Inlet boundaries	342	Outlet boundaries
	Saturation layer	m	1		76	

Hydraulic conductivity, specific yield, surface recharge rate and general head boundary (GHB) inputs were the main parameters in the calibration mechanism and the important factors of the flow movement in a porous media. The highest hydraulic conductivity was obtained in the middle parts of the plain about 11 m/day and the lowest is estimated at about 1.5 m at the aquifer boundaries. Hydraulic conductivity and hydraulic head at the boundaries are the two main factors of groundwater flow in or out of the aquifer. The similar pattern has also been estimated for specific yield (from 0.008 to 0.06) in unsteady state simulation. More details were presented in Table 3.

3.2. Underground dam strategies

According to the mentioned characteristics for locating the construction of an underground dam, the first proposed point is the point UD1 in Fig. 2. This point in the outlet of the plain has created the favorable conditions which is the path of surface and underground flows, has a high hydraulic conductivity (more than 7 m/day) and the volume of reservoir storage and access to water.

Two coefficients must be used to create an underground dam in the model such as the ratio of hydraulic conductivity of the dam to its thickness and the side of the dam in the cell. Fig. 5 shows the groundwater level in a situation that the hydraulic conductivity of the dam is considered zero. The contour lines of the groundwater level after dam construction (Fig. 5) in

comparison with the initial conditions (Fig. 2) showed that the accumulation of water behind the dam by 2.6 m. By moving away from the dam site (point UD1), the height of the accumulated water decreases and finally reaches zero at a distance of about 12 km.

Therefore, the influence distance of the dam constructed with the mentioned conditions in a period of 5 years will be 12 km and the average height increased to the water table will be 1.5 m. Moreover, in case of 25% effective porosity of the porous media, water height equal to 37.5 cm was added to the effective range. To analyze the impact of the underground dam construction, 10 points at different distances from the dam site is considered to control the water table, which are shown in Fig. 5.

At these points, three different heights (without dam effect (S0), 50% flow barrier (S50), and 100% flow barrier (S100)) are compared. Fig. 6 shows points 1, 2 and 3, which have the closest positions to the dam with 0, 2 and 6 km, respectively, adding a height increase of about 2.4, 1.2 and 0.3 to the initial level. More information for other points and conditions is given in the figure.

As shown in Fig., the points of 6, 7, 8, 9 and 10 were not affected. The second location under consideration for the underground dam is point UD2 in Fig. 2, which has been selected and analyzed for the following reasons: 1) It is in the direction of groundwater outlet flow but does not completely block the aquifer outlet; 2) Access to the reservoir is suitable due to the water requirement of the reservoir area because a large part of agricultural and urban extraction wells are located in it; 3) Hydraulic

parameters of porous environment such as hydraulic conductivity, specific yield, transmissivity are acceptable for underground dam construction. The aquifer inlet from the south provides a significant amount of aquifer recharge, which can be used effectively by creating a barrier in this direction.

Fig. 7 shows the water level curves that represent the accumulation of water behind the dam. The difference between this place and the previous one is that the water table after the dam can also be analyzed. Points 1 and 9 show the height of the water table in front of and behind the underground dam, respectively. Point 1 has increased

the height of the water table after the construction of the dam by 5.8 meters (Fig. 8). This value is more than two times of the same as in the previous scenario.

The reason was due to the appropriate choice of location, the movement of the south stream to the outflow boundary and the location of the extraction wells in areas far from the center of the dam. The effective radius of the dam reaches up to 9 km upstream. This volume of water can be used in extraction wells in summer. According to Figs. 7 and 8, the positive effect of constructing an underground dam can be find to maintain groundwater in accessible areas.

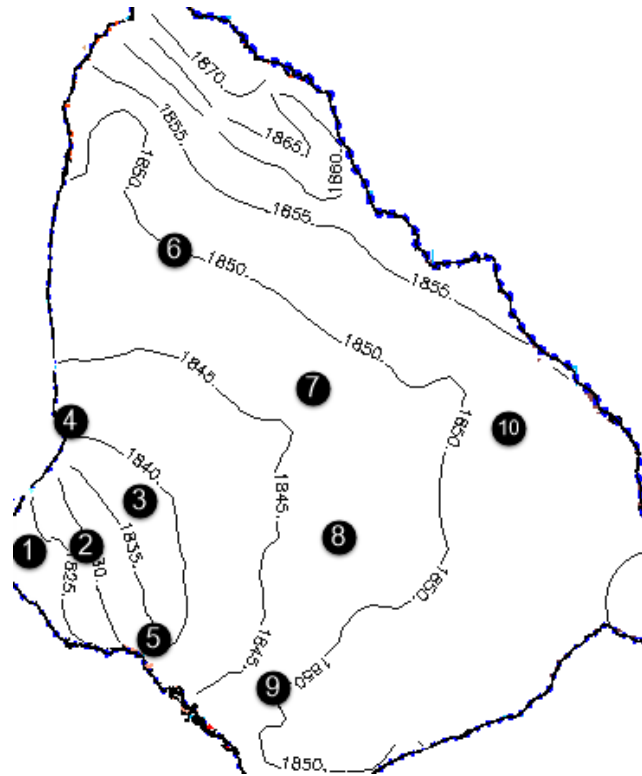


Figure 5. Groundwater level with underground dam in UD1

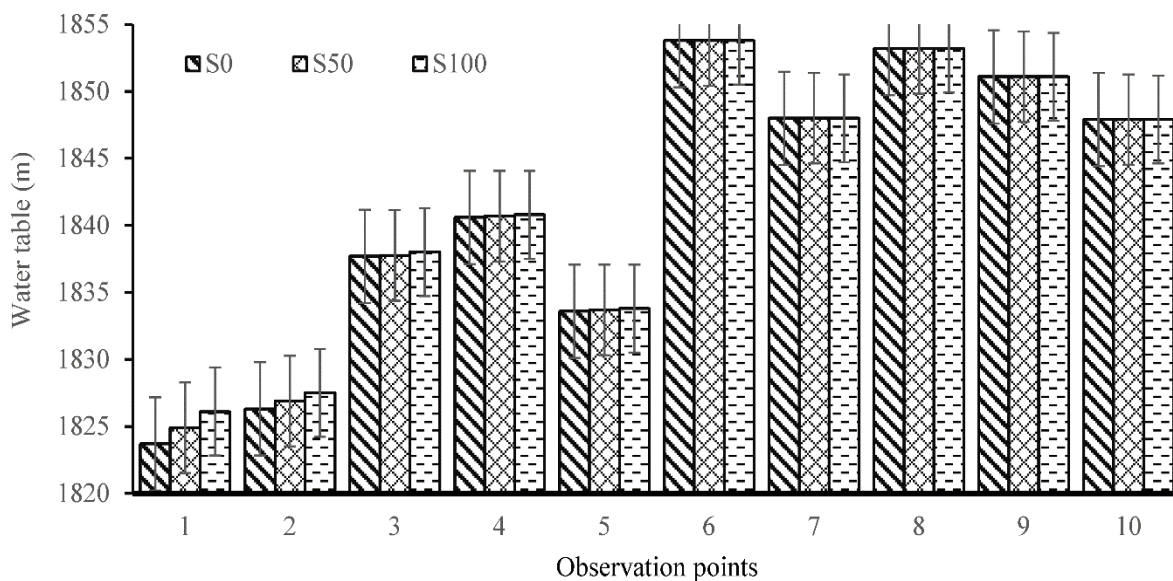


Figure 6. Water table after underground dam construction for location UD1

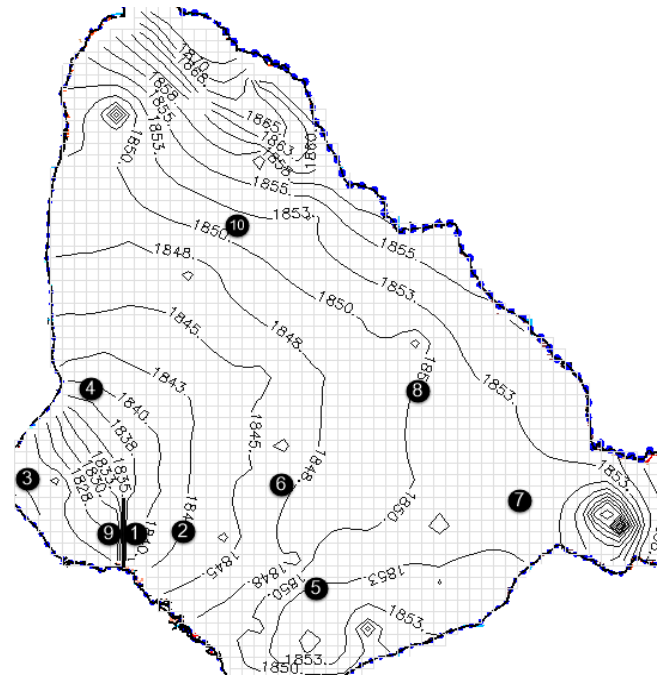


Figure 7. Groundwater level curves under underground dam condition

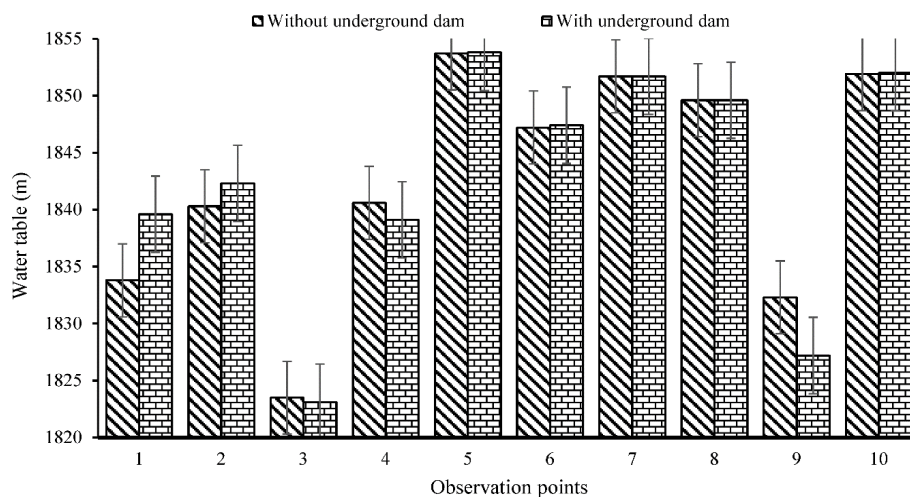


Figure 8. Groundwater level changes with/without underground dam in UD2

4. Conclusion

The range of hydraulic conductivity varies from 1.5 to 11 m/day, which indicates loamy soil in most areas of the plain with significant transmissivity. The specific yield values of Khatoon-Abad aquifer change between 0.008 and 0.06 for near the impervious boundaries and central parts of plain, respectively. The most important source of aquifer storage capacity was the inflows from the northeastern and southern boundaries of the plain and the largest water consumer in the plain was agricultural land. Groundwater inflow was estimated at 48 MCM and the volume of water consumed in the agricultural, industrial and urban sectors were 51 MCM, which is extracted through the model results. Two locations were considered to study the effect of the underground dam considering the availability of water, the volume of stored water and the

porous structure which the UD2 had the better conditions for implementation. The height of water rise and the effective radius of the dam in these conditions was estimated about 5.8 m. Moreover, the first point downstream of the dam after five years will face a reduction in water level of 4.9 m.

Underground dam can be justified due to the large volume of extraction in upstream of the hypothetical structure. While keeping water in the basement prevents water loss downstream and evaporation relative to the dam on the ground.

The difference in water level in other places in the figure shows the positive effects of the construction of the dam in this area. The main factor in determining the effect and location of construction of underground water storage structures after quantitative flow studies was to discuss water quality and prevent pollution. Therefore, it was

suggested to study and analyze the effects of different pollutants through qualitative simulation.

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Authors Contributions

Conceptualization: R.GH
Data curation: R.GH
Formal analysis: R.GH
Investigation: R.GH
Methodology: R.GH
Project Administration: R.GH
Resources: R.GH
Supervision: R.GH
Validation: R.GH
Visualization: R.GH
Writing—original draft: R.GH
Writing—review & editing: R.GH

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Competing Interest

The author declares no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval

Not Applicable.

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