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Exploitation Management of Underground Dams by Using Mathematical Models of Finite Difference in GMS7.1 (The Case Study of Sanganeh Underground Dam-Iran)

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ABSTRACT

Being located in an arid and semi-arid climate, the scarcity of surface water, and the growing population have caused the use of underground dams for storing groundwater to flourish in Iran over the last 10 years. So that at the moment, several underground dams have been built in different areas in Iran. One of the most important issues about underground dams and any hydraulic structure in general that is built for storing water, is exploitation management. Thus in this research, by applying mathematical modeling process, first through basic studies, conceptual model of underground dams in GMS7.1 software was created by the help of vector and raster data produced by GIS software. In the next step, after determining model networks, boundary conditions, and the necessary data input such as hydrodynamic coefficients of underground dam reservoir and recharge and discharge rates, the model was applied by the use of Modflow module in GMS7.1 software. Then, considering the observed well and comparison of the conclusions from water level resulting from the model and observed figures, calibration step of the model was done. After preparing the calibrated model, the authenticity of the model's data was assessed and after verifying the accuracy of the model's results, through applying 4 scenarios, groundwater level changes in the underground dam reservoir was investigated for exploitation management. In the 1 to 3 scenarios by assuming the change in the recharge rate due to rainfall at the predicted time, the maximum operational rate, permitted from the existing operational well in the reservoir, was suggested. In the fourth scenario, the appropriate place for building other operational wells whose maximum exploitation rate permitted is more appropriate than other areas of reservoir, was suggested.

KEY WORDS: Underground dam, Exploitation management, Mathematical model of finite difference, GMS7.1.

INTRODUCTION

Due to the lack of surface water in vast areas in Iran, managing groundwater resources is of great importance. The aim of management of groundwater in an area is the greatest possible use of groundwater for the needs of consumers within and probably out of the area under study [5]. Simulation models of groundwater are one of management tools that nowadays play a decisive role in development and application of policies and adequate and reasonable measures of groundwater [10]. The use of computer models of groundwater has considerably progressed as a cheap and fast way in investigation of motion, balance and exploitation management in recent decades [4]. Among the models with very good capabilities in studying groundwater is McDonald and Harbaugh finite difference model with the name of Modflow which was presented in 1988. This model has been widely used in different issues concerning groundwater by scholars all over the world. As an example, it can be referred to a research that Gupta [8] applied the finite difference model by the use of Modflow software, for flow analysis in underground dam reservoir and estimation of the reservoir volume in Phuket Island in Thailand. Emace et al. [6] developed a 3D model for upper and middle Trinity aquifer in the region of Hill Country in the south of Texas in America aiming at identifying hydrogeological system and assisting to estimation of water amount and water level fluctuations in relation to pumping and potential drought in future. For this, the numerical model Modflow 96 was used. In this research, calibration was done in steady state for the conditions of 1995 and in transient state for conditions of the years 1996 and 1997. In addition, by the use of this model, the amounts of vertical hydraulic conductivity and storage coefficients for aquifer calibrated. Water level showed the greatest sensitivity to feeding, horizontal hydraulic conductivity of the mid-layer and hydraulic conductivity of the upper layer. Todd et al. [15] simulated groundwater of this region by Modflow software for identifying the range of drinking water in Sturgeon Bay in Wisconsin in America. They performed the model in two states of steady and transient. Finally, due to the results obtained from the model and their comparison with the observed data, they concluded that the application of the model in transient state for the above region, presents better reflection of the aquifer behavior. Katibeh and Hafezi [9] simulated the groundwater of Abe-e Barik plain in Bam in Iran with Modflow software and concluded that the function of aquifer artificial feeding design with the help of flood distribution added 12.6 million cubic meters annually to the aquifer storage. Thorley et al. [14] modeled groundwater of Chris George town in New Zealand by the use of visual Modflow software. For modeling, they used monthly data of 157 drinking water supply wells. They estimated parameters of hydraulic conductivity and feeding rate through reverse modeling and Pest software. Then, they estimated groundwater flow lines by the use of Modpath software and data from 31 selected wells. Rahnama and Kazemi [13] simulated groundwater flow of Rafsanjan plain in Iran by the use of Modflow and investigated the effects of the drop of groundwater level on land subsidence in this field. Nejati et al. [12] used GMS6.5 software which was based on finite difference model of Modflow 2000 for investigating the impact of drought in 2007-2008 on Aghili plain in Iran. In this research, the comparison of the results of the model with plain unit hydrograph showed the very high accuracy of the model's prediction in drought conditions and application of different management scenarios. Akbar pour et al. [1] managed the exploitation of groundwater of Mokhtaran plain by the use of mathematical model of finite difference in GMS6.5 software. In this research, the reaction of the aquifer in exploitation conditions was investigated by the model. According to the aquifer states, it was specified that any new exploitation from the storage exacerbates the damage process to the groundwater resources in the region and results in further reduction of discharge of existing operational wells and rather leads to noneconomic exploitation of the aquifer.

In this research, for managing exploitation of underground dams, mathematical model of finite difference in GMS7.1 software was used for its high graphic capabilities and data exchange capability with different software such as GIS software. GMS software is a modeling environment which is used for simulating groundwater system. GMS includes a graphical interface and a number of analytical codes such as Modflow.

The features of the region under study

Sanganeh underground dam is located at 5 kilometers from Sanganeh village in the Northeast of Iran in geographical location of 252710N and 4068760E. Regional situation in which the underground dam was built is in such a way that lands are of pasture use, and agricultural lands are very limited and in the form of dry farming. The major regional water need is supplying drinking water for cattle. From the point of view of structural zone classification, the underground dam scope is located in Kope Dagh structural basin. The formations in the Northern part of Ashlir anticline are the major part of geological deposits of the area under investigation. Mesozoic deposits (cretaceous) are considered the oldest geological organization of the region and quaternary alluvial deposits from the newest geological deposits of the region. According to the overall divisions of catchment basins in Iran, the region under study is within Kashafrood catchment basin, one of the 5 basins in Khorasan Razavi and is one of the sub-basins of Kalat-e Naderi catchment basin.

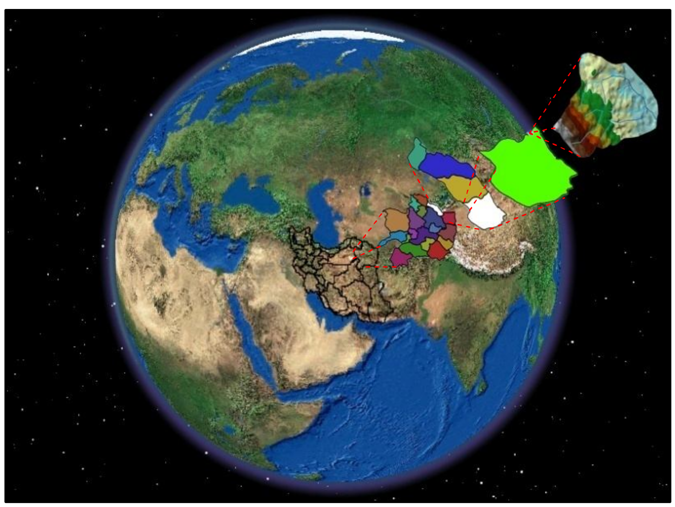


Figure 1: The situation of the catchment basin of the underground dam in Sanganeh-Iran [11]

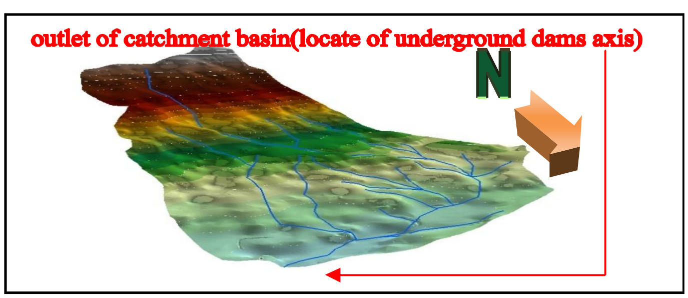


Figure 2: The 3D view of the catchment basin of the underground dam in Sanganeh- Iran [11]

MATERIALS AND METHODS

Mathematical model and GIS were used for investigating groundwater flow system in the underground dam reservoir which is under study. For this purpose, a database was prepared in GIS from all the existing data such as geological, metrological and hydrological data, the results from processing of satellite images, geophysical exploratory investigations, hydrogeological studies and balance. The stored data in GIS database were converted to the conceptual model by the use of GMS7.1 software and then the prepared conceptual model was transformed to the numerical model array and the model was implemented in GMS7.1 software by the use of Modflow module. Figure 3 shows the modeling algorithm for preparing the mathematical model from the conceptual model.

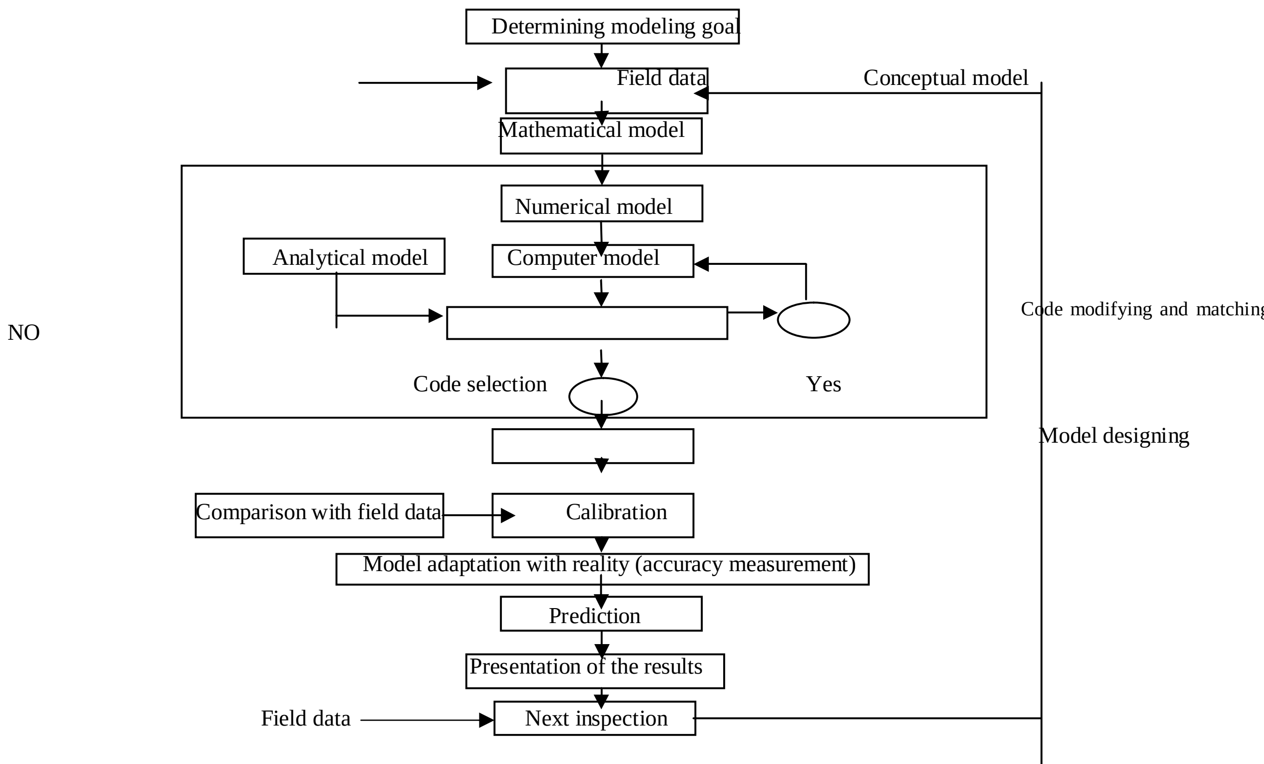


Figure 3: Numerical modeling algorithm [16]

DISCUSSION

The modeling method, used in this research has been presented consistent with modeling protocol over different stages, has been selected and implemented by Wang and Anderson [16]. Modeling protocol includes all the preparation steps of a model; that is, determining the purpose, preparing the conceptual mode, formulating the mathematical model from the conceptual model, model network designing, calibration, measuring accuracy and finally predicting and applying managing scenarios which were done as follows:

Conceptual model

According to the modeling process, after identifying the goals of the model and doing the basic studies, preparing the conceptual model is essential as a prerequisite to the mathematical model in this stage. Preparation of a conceptual model in this research includes determining the geometry, type and ingredients of the underground reservoir, the way of the reservoir relation with the surrounding geological formations and surface water collections, hydrological boundaries identification and limits, feeding and discharge sources and groundwater flow system. In this line, the conceptual model was prepared by using the field studies done, satellite images, the results of geophysical and penetration tests and hydrological and metrological data and statistics. On the base of the studies done, the topography of reservoir surface with the slope of about 2 percent stretches from the Northwest to Southeast. The Northern and Southern boundary of the underground dam are made of fine grain limestone (Abderaz formation) and gray shale (Sanganeh formation) and form the pickets of the underground dam axis. They are of low permeability. In the conceptual model, they are considered as impermeable boundary. The eastern boundary of the reservoir which is the place of the underground dam axis was considered as barrier boundary, and the western boundary which is the site of the groundwater to the underground dam reservoir was regarded as specified flow boundary. According to geophysical studies which have been done in consistent with geoelectric method in the reservoir by 41 geoelectrical sondages, the bed rock is made of marly clay and marly shale which has been considered as impermeable lower boundary. The depth of the bed rock is 10 meters in the place of the dam axis and becomes about 30 meters at the end of the reservoir. There are totally three alluvial layers (one surface layer and 2 subsurface layers) in the underground reservoir. The surface alluvial layer is mostly made of gravel with the thickness of between 1.5 to 2 meters throughout the reservoir. Subsurface alluvial layers contain 2 layers made of different materials such as sand, silt, clay and … And they are in Interfingering state. The second alluvial layer has the thickness between 2 to 5 meters and like the first layer exists all over the reservoir. The third layer, which exists only in the end sections of the reservoir, has the maximum thickness among the layers of the reservoir so that its thickness is between 10 to 30 meters. The recharge rate from rainfall has been extracted from the rainfall statistics measured in the reservoir and due to the small range of the model, it has been considered consistent in all the levels of the reservoir. According to the data from the observed wells and preparing Isopiez map, the direction of groundwater flow complies with the topography steep of the reservoir and it goes from the Northwest to the Southeast.

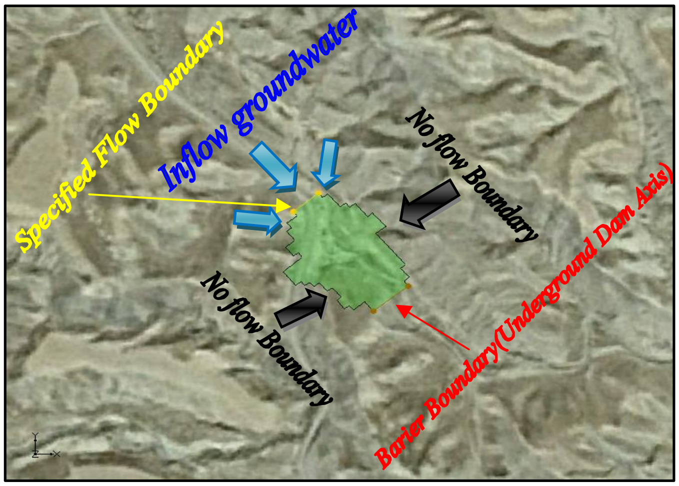


Figure 3: Two dimensional conceptual model of the Sanganeh underground dam reservoir -Iran [11]

Mathematical model

A model of groundwater is in fact a simplified form of a real groundwater system which approximately presents correlation between hydrodynamic action and reaction. The aim of creating a mathematical model in the groundwater aquifer is the natural simulation by using a series of mathematical relations. Mathematical model contains writing a program or a computer code which has been given to GMS software. This part includes model designing and interpreting the conceptual data model and its transformation to the code of Modflow 2000. The governing equation in this modeling is Poisson equation in the 3D state which is as follows:

$$\frac{\partial}{\partial x} h \frac{\partial h}{\partial x} + \frac{\partial}{\partial y} h \frac{\partial h}{\partial y} + \frac{\partial}{\partial z} h \frac{\partial h}{\partial z} = Sy \frac{\partial h}{\partial t} \pm \frac{R}{2Kxy}$$

In this formula, K_{xy} is the component of hydraulic conductivity in x, y directions, $\frac{\partial}{\partial x} h \frac{\partial h}{\partial x}$: the second-order partial derivative of hydraulic load toward x, $\frac{\partial}{\partial y} h \frac{\partial h}{\partial y}$: the second-order partial derivative of hydraulic load in the direction of y, $\frac{\partial}{\partial z} h \frac{\partial h}{\partial z}$: the second-order partial derivative in z direction, S_y: Specific yield and R: recharge (+) or discharge (-) component of the aquifer. To create mathematical model of Sanganeh underground dam reservoir, networking stages, determining boundary conditions, hydraulic coefficients input, initial conditions and estimation of supply rate were done. These steps are as follow:

Model networking

Networking is done after preparing the conceptual model. In order to be able to solve partial differential equations for groundwater, the environment should be divided into smaller parts which is commonly called network. In finite difference method, the studied area is divided into some rectangular or square network, by two sets of parallel lines perpendicular to each other. Certainly, the smaller the networks dimensions are, the more the number of networks becomes, and the accuracy of computation increases, while the volume of computational operations and work amount for preparing the data will be far more.

In the region under study, according to groundwater basic data, the form of the reservoir, and the reservoir geographical direction, the model network was circulated as much as 40 degrees in the clockwise around the z axis, in order that the underground dam axis (Eastern boundary) and the entrance of the groundwater to the reservoir (Western boundary) be situated perpendicular to the groundwater flow direction. Due to the small extent of Sanganeh underground dam reservoir with 220 meters length and 170 meters width, and also the number of sondages, and their distance from each other, the network dimensions were considered 10×10 square meters. So that 17 cells were considered in the width and 22 cells in the length that totally formed 374 cells on the reservoir surface. Moreover, in the third dimension; that is, along z axis, number 3 was selected as the number of cells along z due to the existence of 3 alluvial layers.

Determining boundary conditions

After the model networking, the boundaries of the model should be identified. As previously in the part of the conceptual model, system boundaries were defined, in this part by using the conceptual model module in GMS7.1 software, each of the system boundaries is drawn and the data enter the prepared network. As it was mentioned, the Northern and Southern boundaries entered the model as impermeable boundaries, the Eastern boundary as the barrier boundary and the Western boundary as specified flow boundary. By applying the boundary conditions, the cells introduced to the model as impermeable cells are identified with the code 0 and are excluded from software calculation process. Other cells in the network are identified with code 1 in the model and are computed.

Hydraulic coefficient input

In this stage, through the data from pumping tests on a borehole which had been dug in the underground dam reservoir and also geophysical logs and standard tables [3], the aquifer hydrodynamic coefficients were provided in the initial form and entered the model.

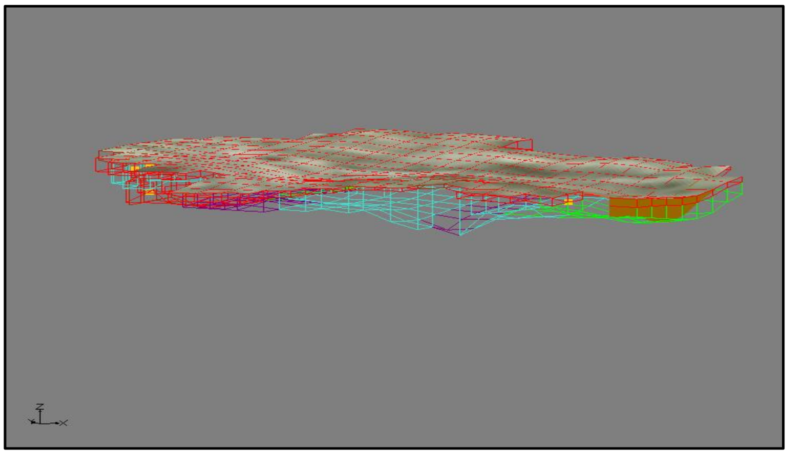


Figure 4:3D view of the reservoir of Sanganeh underground dam -Iran [11]

The initial conditions

For login the initial hydraulic head to the model as the starting head, water level data from seven wells within and around underground dam reservoir related to February 2011 have been used as the origin of simulation.

Recharge of Sanganeh underground dam reservoir

As in the scope of Sanganeh underground dam, there are no lands for agriculture or industry, recharge is only of the natural kind. The most important factors of natural recharge of underground dam reservoir under study are the input of underground flow and infiltration of running water from rainfall in non-permanent stream context in reservoir level. Considering the length, hydraulic slope and the reservoir transferring capability, the rate of the underground flow entered to the reservoir has been computed 63.1 m^3/day and entered the model. According to the rainfall statistics and assuming 20 percent permeability, the running water penetration rate from rainfall has been initially considered 0.0001m/day.

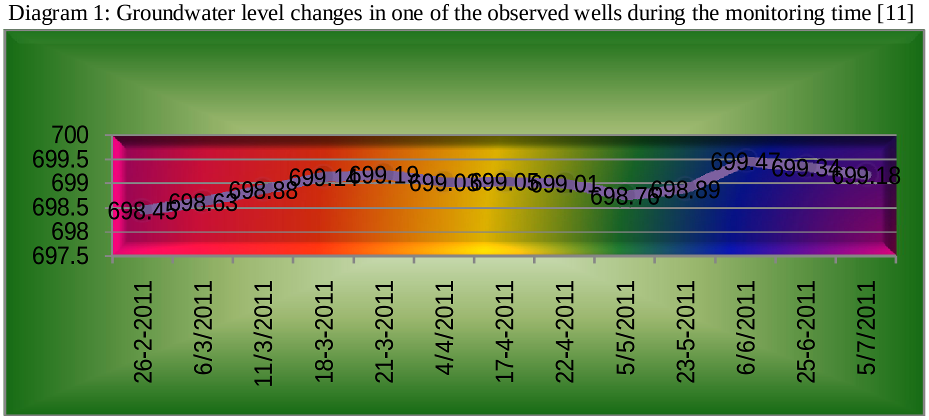
Running the model

To run the model, according to the purpose, the origin of time and the duration, simulation should be specified. In this research, because of the data range of the groundwater monitored is limited, a 30-day period was considered as the period of simulation in the steady state and a period of 129-day as the period of simulation in the transient state. Due to the changes of the groundwater level in the observed wells over this period (diagram 1), 5 stress periods with unequal lengths were considered for simulation in the transient state (figure 5). Following the model was implemented first in steady state and then in the transient state.

Model calibration

Calibration means minimizing the difference between the observed and computed amounts by the model. To calibrate a model, first the parameter which is considered for calibration should be specified. Normally the parameter which is used for calibration is the groundwater level because its measurement is easier than other parameters, it has also fewer errors and its calibration is easier, too. As according to the observed wells data, the groundwater level changes have been between 15 to 80 centimeters during the monitored period, so according to the expert, the rate of the acceptable error in calibration was considered 25 centimeters. To present the calibration process, GMS software uses colored rods in observation points which represent the rate of calibration error and its center matches the observed amounts (figure 6). If the error is less than the acceptable error, the rod will be green and if it is more than the acceptable error (25 centimeters) and less than 200 percent of the acceptable error (the difference between the observed and the computed water levels is less than 50 centimeters) the rod will be yellow and in case the error rate is more than 200 percent of the acceptable error, the rod will be red. Due to the difference between the observed and computed water levels after running the model in steady state, through trial and error method and performing trivial changes in hydraulic conductivity parameter, the model was frequently implemented until a proper fitting achieved between the observed and computed water levels. After that, this time the model was implemented in transient state and was calibrated. In this stage, the computed water level which has been calibrated should be transformed as the starting head from the steady state to the model in the transient state. To calibrate the model in transient state, instead of performing trivial changes in the rate of hydraulic conductivity parameter, the model is calibrated with trivial changes in other parameters such as S_y or recharge through trial and error.

Diagram 1: Groundwater level changes in one of the observed wells during the monitoring time [11]



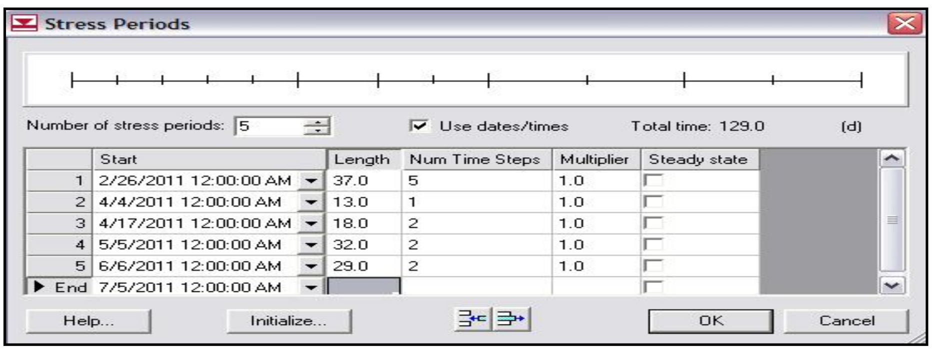


Figure 5: The considered time period for simulation in transient state [11]

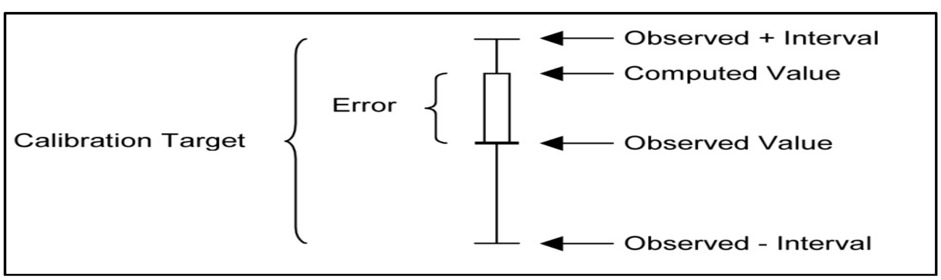


Figure6: Calibration Target in GMS [7]

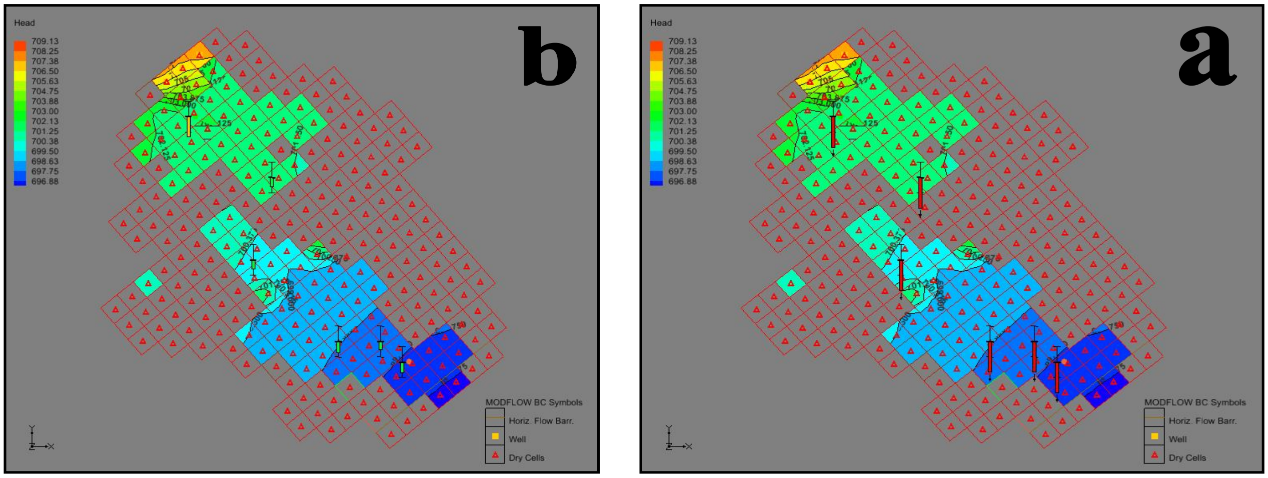


Figure 7: Model status after application in steady state: a) before calibration, b) after calibration [11]

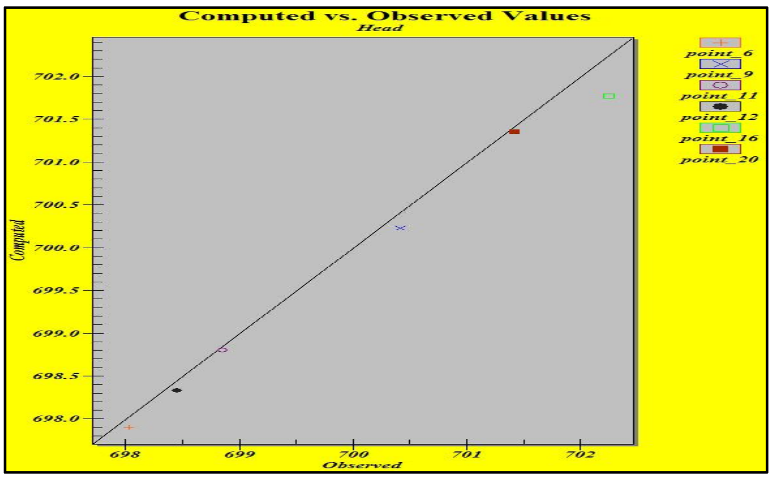


Figure 8: Comparative diagram between the observed and computed water levels after calibration in steady state [11]

Table 1: The rate of computed water level by the model and the observed water level in observation points [11]

View Values

	point_6		point_9		point_11		point_12		point_16		point_20	
	Observed	Computed	Observed	Computed	Observed	Computed	Observed	Computed	Observed	Computed	Observed	Computed
1	698.03264119608	697.8986	700.41094213122	700.2293	698.86159234411	698.8012	698.45320755103	698.3298	702.24952893439	701.7695	701.4251817217	701.3505

Close

Accuracy measurement of the model

To make sure about the accuracy of the results of the calibrated model, the model should be implemented in the interval other than the one that the model was calibrated and the results be compared with the observed results. For this purpose, the data related to the observed water level in August 2011 was used and the model was implemented in this interval. As the difference between the observed and computed data was within the acceptable limits, the model accuracy was verified and the model entered the phase of prediction and implementation of management scenarios.

Conclusions

After the model calibration and confirmation of the model accuracy, the time from October 2011 until May 2012 (the annual time period of water needs of the region under study) was considered as prediction period and finally through performing some scenarios, the system interactions in relation to the managing conditions applied for exploiting the underground dam were investigated. In these scenarios, the maximum rate of exploitation from the existing operational well in the reservoir (the well number 0 in figure 9) with applying changes in recharge rate and also the placement change of the operational well were investigated.

The first scenario

In this scenario, it was assumed that the recharge rate over the prediction period is similar to recharge in model simulation period. As the result of applying this assumption, the maximum rate of exploitation of the existing operational well suggested is 7.56 m^3/day for pumping per hour by a pump engine with the power of 4 lit/s.

The second scenario

In this scenario, the recharge rate over the prediction period was assumed 10 percent less than recharge in the model simulation period. As the result of applying this assumption, the maximum rate of exploitation of the existing operational well suggested is 6.9 $m^{3/}$day for pumping per hour by a pump engine with the power of 4 lit/s.

The third scenario

In this scenario, it was assumed that the recharge rate over the prediction period is 10 percent more than recharge in the model simulation period. As the result of applying this assumption, the maximum rate of exploitation of the existing operational well suggested is 8.16 m^3/day for pumping per hour by a pump engine with the power of 4 lit/s.

The fourth scenario

In this scenario, due to the possible potentials of exploitation of the underground reservoir, considering the new areas of exploitation, their spatial distribution and maximum discharge were investigated. Finally, two areas which had the probability of new exploitation potential were selected. The most important criteria for selecting these areas were appropriate and great thickness of the reservoir in new exploitation areas and that in two parts of the reservoir the conditions were observed and according to the model results of two operational wells with number 1 and 2 were placed in these areas (figure 9). The suggested well number 2 was placed in the end parts of the reservoir. The thickness of the reservoir was about 30 meters in these areas. So, very high exploitation of this well was expected and that the model result in this well confirmed this assumption such that the maximum rate of exploitation of this well was obtained about 70 m^3/day per 12 hours exploitation.

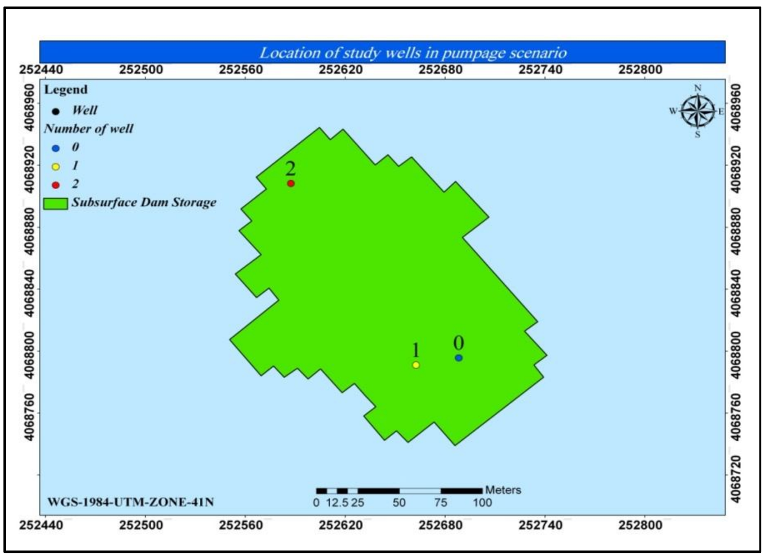


Figure 9: The existing operational well status (number 0) and the suggested wells (numbers 1 and 2) [11]

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