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APPLICATION OF NUMERICAL MODELING TO PREDICT AND EVALUATE THE EFFECTS OF MANAGEMENT SCENARIOS IN GROUNDWATER RESOURCES

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ABSTRACT

Using numerical models, it is possible to predict with the governing process or different management scenarios, how the aquifer reacts to abstraction and recharge. In this study, the hydraulic behavior of Varamin Plain aquifer was simulated using the MODFLOW code of GMS software. The main aim of this simulation is to evaluate the effect of current aquifer management plans and the Jajrood River basin on changes in the water table of the unconfined aquifer and the piezometric level of the confined aquifer. After calibrating the model, the hydrodynamic coefficients were corrected and then using the obtained model, the quantitative behavior of the aquifer was predicted for two management scenarios for the future years. The results of the study showed that the implementation of recharge and discharge management plans can only lead to a decrease in groundwater level in the aquifer if it does not significantly reduce the percentage of water entering the aquifer.

Disciplinary: Hydrology Engineering, Groundwater Engineering.

1. INTRODUCTION

Nowadays, groundwater is considered as a vital and strategic water resource for people living in the arid and semi-arid regions. Therefore, the study and management of the aquifers in the low-water areas have become a dynamic field of study in recent years (Al-Shaibani 2008). Most of the cities in Iran are located in areas where people do not have access to surface water; therefore, the main water source in these areas used for drinking and agricultural purposes is groundwater. One of the consequences of long-term and immethodical abstraction of groundwater is a reduction of the water table in the plains, which causes the land subsidence phenomenon. The land subsidence phenomenon has become a major concern in Iran and across the world. Land subsidence is one of the natural hazards, which occurs vertically in most cases and is not apparent during a short period of time. Inattention to this phenomenon leads to irreparable damages; therefore, the future behavior prediction

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of the aquifer to abstraction is very important (Foster et al. 2013). In fact, predicting areas of the aquifer, which are more vulnerable, is a powerful tool for the optimized management of the groundwater resources. Today, using models to illustrate the facts and better understand the facts, as well as to make accurate decisions about phenomena is very common. One of these models is the simulation model of the groundwater flow used by experts in many countries, which has affirmed the accuracy and validity of their results (Harbaugh 2005). Groundwater numerical modeling is an important tool to manage aquifers. These models can be used to estimate the hydraulic parameters and also to manage water resources (Regli et al. 2003). Using numerical models, it can be predicted how the aquifer reacts to abstraction and recharge with the governing process or different management scenarios. Today, quantitative simulation of groundwater has been expanded via MODFLOW code using pre and postprocessor software. MODFLOW code has been used for groundwater flow simulation in various parts of the world, including the Nile Valley aquifers in the Tahta area and the Central Delta in Egypt (Shamrukh et al. 2001; Ghoraba et al. 2013), aquifers in the Croydon basin (one of the most important agricultural production areas in Europe), Cumbria area in France (Mol´enat and Gascuel-Odoux 2002; Serhal 2009), Sumas Blaine aquifer in Washington State, USA (Almasri and Kaluarachchi 2007), Willmore River Basin on Edmonton Canadian Island (Jiang and Somers 2009), Sherwood aquifer in West Nottingham Shire, England (Zhang and Hiscock 2011), Thessaly area in Greece (Stamatis et al. 2011), and Zagreb alluvial aquifer in Croatia (Marković et al. 2013). Since 50 years ago, Varamin Plain has always been the focus of attention due to its significant economic and social capacities, especially in the development of agricultural and industrial activities. Groundwater quantitative assessment of Varamin Plain is important because it supplies a large amount of agricultural and drinking water. In this study, the hydraulic behavior of Varamin Plain aquifer was simulated using the Modflow code of GMS software in stable and unstable states. The main aim of this simulation is to evaluate the effect of current aquifer management plans and Jajrood River basin on changes in the water table of the unconfined aquifer and the piezometric level of the confined aquifer in Varamin Plain. After calibrating the model, the hydrodynamic coefficients of the plain were corrected and then using the obtained model, the quantitative behavior of the aquifer was predicted for two management scenarios for the future years. Considering that the unstable simulation period of the model ends in the 2008 water year, implementing the model in future conditions has been carried out from this year onwards, from 2009 to 2041.

2. MATERIAL AND METHOD

2.1 THE STUDY AREA

Varamin plain is situated in the southeast of Tehran plain and northwest of the central desert of Iran. This plain is located in the southern slopes of the Alborz Mountains, northern Iran. The study area is about 1595 km2. The study area is situated between the longitudes of 55° 29′ and 56° 08′ and latitudes of 28° 49′ and 29° 58′ (Karami et al. 2017). The annual average rainfall is approximately 172 mm and the evaporation rate is roughly 2439 mm per year. The climate of this area is dry to semi-dry, but the southern part tends to be hot and dry due to its location in the desert border (Mokhtari and Espahbod 2009). The average altitude of the area is 1024 m. Figure 1 shows the location of Varamin Plain in Iran and in Tehran Province.

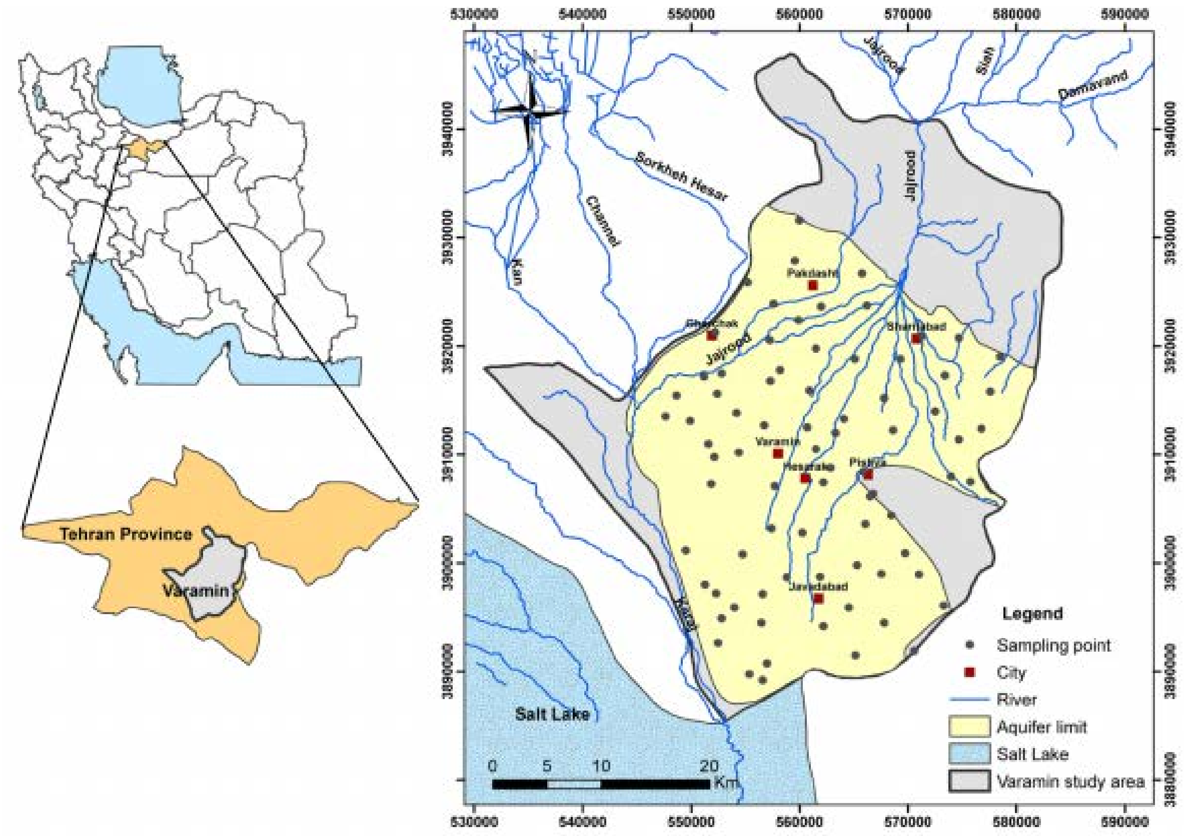

Figure 1: Geolocation of Varamin Plain in Tehran Province (Iran).

2.2 VARAMIN AQUIFER MANAGEMENT PLANS AND JAJROOD RIVER BASIN

The ever-increasing development of Varamin Plain led to the exploitation of water resources development plans, including the plan of irrigation network and drainage of the plain, Varamin diversion dam, artificial recharge plan of the aquifer and Varamin canal. However, under current conditions, the water crisis caused by the immethodical abstraction of groundwater has increased and affected the region. In future years, with the complete exploitation of Mamlou storage dam, artificial recharge plans of Varamin Plain, southeast treatment plant of Tehran, increasing the capacity of Varamin Canal, and changes in the allocation plan of Latyan storage dam, Varamin Plain will encounter various changes in the quantity and quality of aquifer storage. In general, the effects of the implementation of each of the mentioned plans on Varamin aquifer can be summarized as follows:

- The implementation of Mamlou storage dam and the transfer of 120000000 m^3 to supply drinking water of Tehran which will bring about the decrease in the water entering through Jajrood River at the entrance to Varamin Plain.

- Complete exploitation of the south treatment plant of Tehran and increasing the capacity of transferring Varamin Canal, which will allocate 203000000 m^3 water to the Varamin irrigation network and 65000000 m^3 water to artificial recharge plans including basins No. 2, 3, and 4 of Varamin Plain.

Simulation of the Varamin Plain aquifer was carried out for two stable and unstable states. After calibrating and preparing the final model, two different scenarios, one without the above management plans and the other based on the two above management plans, were applied for the model to assess the response of the aquifer to these two plans in the future years. The evaluation process performed in these two scenarios is examined.

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2.3 AQUIFER SIMULATION SCENARIOS

In order to predict the aquifer quantitative situation in the future years, two scenarios are considered. The purpose of these scenarios is to assess the implementation effect of water resources development plans on Varamin Plain. The first scenario is related to the continuation of existing conditions. This scenario, which has the same boundary and initial conditions as the simulated situation, indicates the current quantitative situation of Varamin aquifer. That is, if the current situation continues, Varamin aquifer will encounter certain risks in the future years. The second scenario indicates the situation of the aquifer if the plans are carried out by the relevant organizations. Under these conditions, the assigned values from the discharging of the southeast wastewater treatment plant of Tehran enter the study area and due to the implementation of the Mamlou storage dam, a significant portion of the surface water resources of Jajrood River will not enter the study area. Therefore, in the horizon of the plan, about 203000000 m^3 of discharging of Tehran wastewater treatment plant will be allocated to agricultural purposes in Varamin plain, and about 65000000 m^3 will be transferred to artificial recharge in basins No. 2, 3, and 4.

2.4 SIMULATION OF THE GROUNDWATER FLOW

GMS software (Ver: 7.1) was used to simulate the groundwater flow of Varamin aquifer. The steps of the model implementation involve the gridding of the study area, spatial and temporal classification, the definition of the model boundaries, and how to assign the initial parameter values to the various model nodes.

2.4.1 GRIDDING

A mathematical model grid of Varamin aquifer has been designed from the regular and equal-sized cells (500m*500m) and in three separate vertical layers. The number of grids covering the entire extent of the unconfined and confined aquifers is more than 82 rows and 98 columns.

2.4.2 AQUIFER HYDRODYNAMIC COEFFICIENTS

In order to assign the K values to the model cells, the equation $T = K \times b$ was used, where T is transmissibility, K is permeability coefficient and b is the aquifer thickness. It is clear that the permeability coefficient in each cell is equal to the division result of the transmission coefficient by hydrous layer thickness in that cell. The values obtained from this method were corrected during calibration.

2.5 BOUNDARY CONDITIONS AND INITIAL CONDITIONS OF THE MODEL IN STABLE AND UNSTABLE FLOW

2.5.1 BOUNDARY CONDITIONS

Boundaries are classified into two general types including physical boundaries and hydraulic boundaries. Physical boundaries are formed by the physical existence of an impermeable phenomenon or massive body of surface water. Other boundaries such as groundwater division line and flow lines, which are invisible and are formed as a result of the hydrological conditions, are called hydraulic boundaries (Anderson and Woessner 1992).

Varamin Plain aquifer is formed from a hydrous unconfined layer in the northern alluviums, which extends to the middle of the plain. Due to the existence of a less permeable layer between the more coarse-grained alluviums, the aquifer in the southern parts of the plain is divided into two hydrous layers with different hydraulic characteristics. The surface hydrous layer in these parts is the unconfined hydrous layer type and underlying layers are confined (TRWA 2014).

In Varamin aquifer, the actual boundary between the unconfined and confined area is not clear, and this is problematic in determining the confined aquifer. To solve this problem, the hydraulic and hydrodynamic properties of layer 2 (the impermeable layer between two aquifers) and layer 3 (confined aquifer) in the northern part of the plain are assumed to be equal to layer 1 (unconfined aquifer). This means that in the northern part of the plain we will have an unconfined aquifer in the prepared model. The boundary of the unconfined aquifer is defined as a known discharge type, and the boundary of the lower layer is defined as an active cell type. These values have been initially estimated and corrected during calibration (TRWA 2014). Figure 2 shows the assumptive structure of the aquifer.

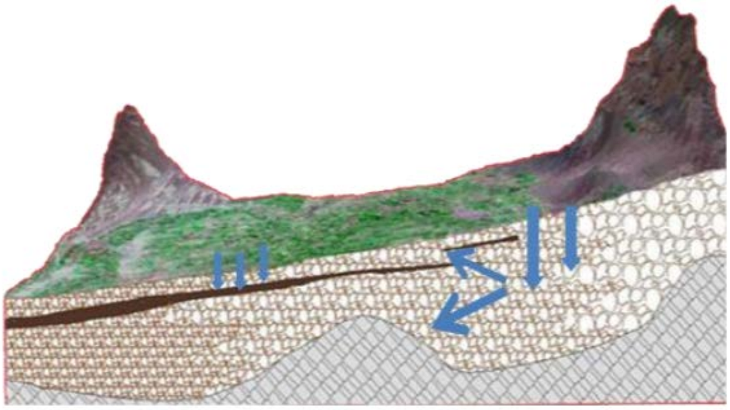

Figure 2: Model structure of Varamin plain aquifer.

2.5.2 INITIAL CONDITIONS

After determining the type of aquifer boundaries, recharge and discharge data from both the surface and underground were imported into various coverages of the conceptual model. In the next step, information of abstraction and piezometric wells were imported. After importing the coverages information, the quantitative model was implemented. Initial conditions of the aquifer to implement the model in a stable state are the same as the groundwater level at the beginning of the adjustment period, early September 2006. Similarly, the model was adjusted and implemented in an unstable state for seasonal stress periods from 2006 to 2008.

2.6 CALIBRATION AND ADJUSTMENT OF THE AQUIFER QUANTITATIVE MODEL

Calibration is one of the most important and most difficult steps in preparing a numerical simulation model for groundwater. PEST is one of the most suitable codes for parameter estimation, created by Doherty et al. (1994) for MODFLOW. This code has a wider application than other existing codes, due to the ease of use and attachment to MODFLOW. For this reason, the PEST code was used for calibration in this research. In the next step, during calibration of the stable state, the permeability coefficient and during calibration of the unstable state, specific yield and storage coefficient of the aquifer were corrected. Based on the simulation results, it was found that the specific yield of the unconfined aquifer varies from 0.03 to 0.20. Also, the storage coefficient of the confined aquifer varies from 0.002 to 0.008.

Figure 3 shows the correlation between observational and computational water level values in the unconfined aquifer after calibration for the summer of 2008. The correlation of the above values is very high (R^2=0.993) and indicates the high adaptation of the model in the unstable flow regime.

Figure 4 shows the correlation between observational and computational water level values in the confined aquifer after calibration for the summer of 2008. The correlation of the above values is very high (R^2=0.987) and indicates the high adaptation of the model in the unstable flow regime.

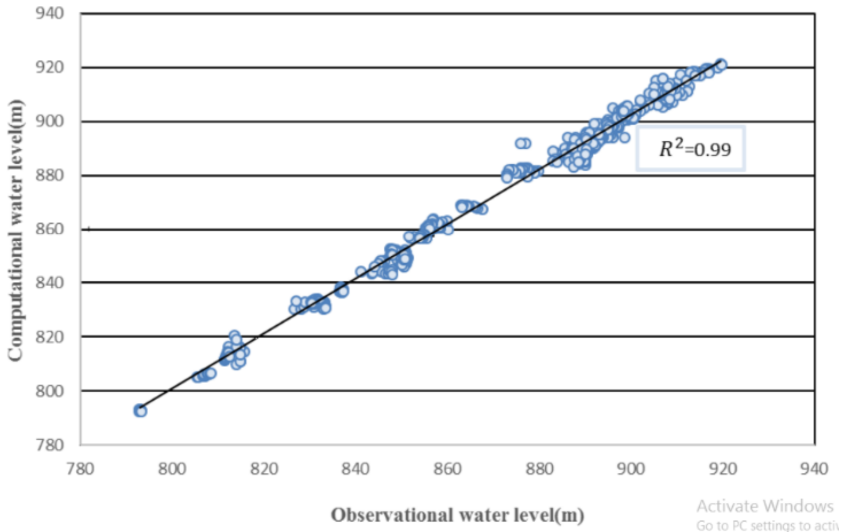

Figure 3: Correlation between observational and computational values of water in observational wells of the unconfined aquifer in unstable flow.

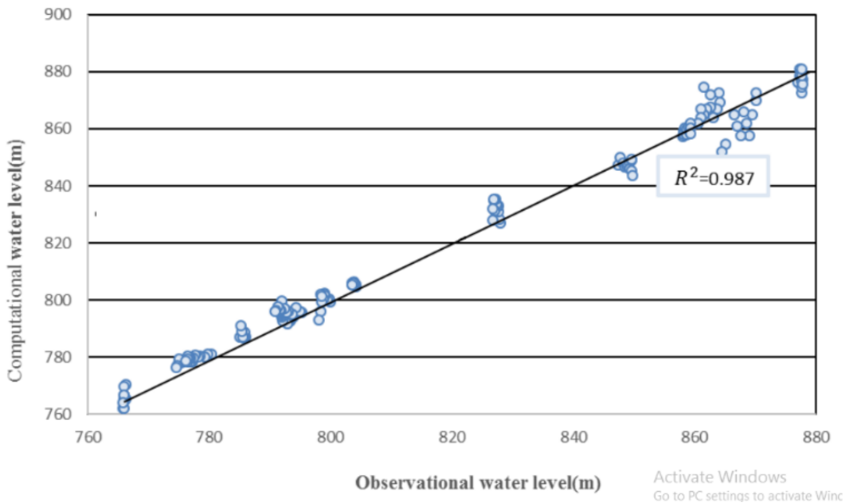

Figure 4: Correlation between observational and computational values of water in piezometric wells of the confined aquifer in unstable flow.

3. RESULTS

3.1 SIMULATION IN AN UNSTABLE STATE

After calibrating the model parameters, simulation results obtained from the model in unconfined and confined aquifers in the unstable state were calculated for different periods and compared to the observed values. Results obtained from the calculations in observational and piezometric wells are consistent with the observed values in these wells. Figure 5 shows the results of the two wells.

The water table isopleth map of the unconfined aquifer, and piezometric level of the confined aquifer in the years 2005 to 2008 obtained from the model are shown in Figures 6 and 7. During this period of time, there were 12 stress periods, and so 12 isopleth maps were obtained.

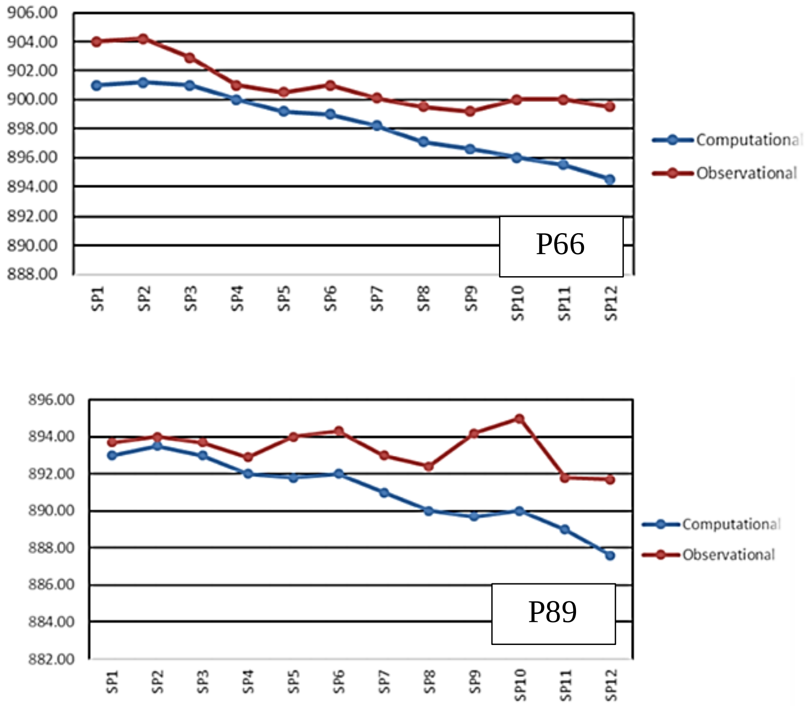

Figure 5. Comparison of observational and computational water levels in observational wells in an unstable period.

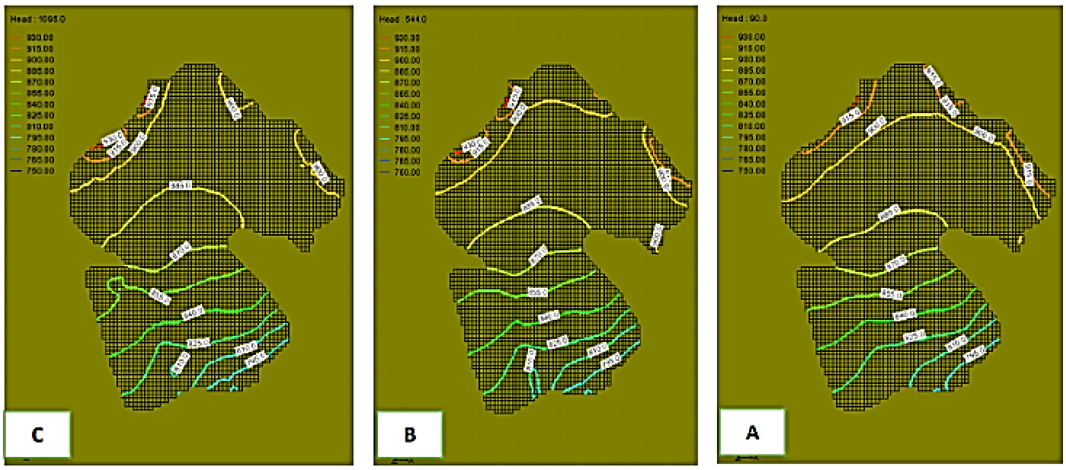

Figure 6. Isopleth lines of the groundwater level in the unconfined aquifer during 3 different stress periods. (A: Fall 2005, B: Winter 2006, C: Summer 2008).

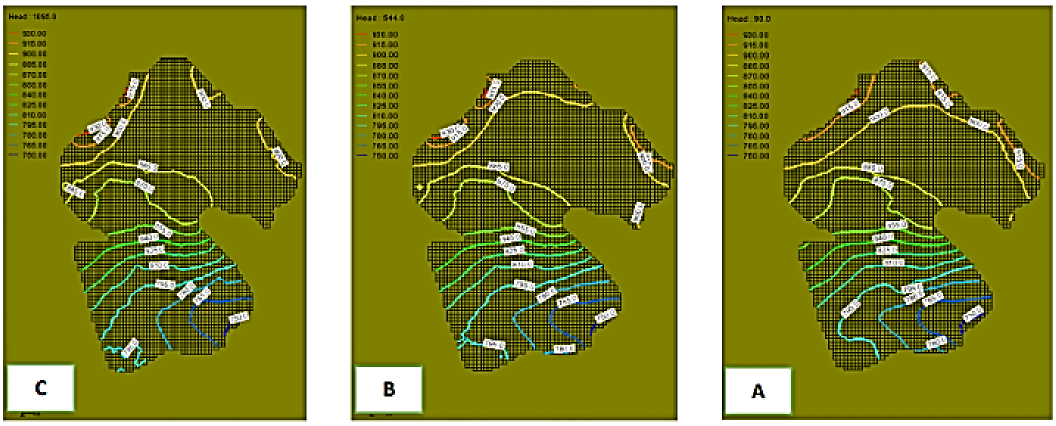

Figure 7. Isopleth lines of the piezometric level in the confined aquifer in three different stress periods. (A: Fall 2005, B: Winter 2006, C: Summer 2008).

3.2 PREDICTING THE QUANTITATIVE CHANGES OF THE AQUIFER IN FUTURE YEARS

In order to import the model data for assessing the reaction of Varamin alluvial aquifer in the future, the prepared model should be readjusted and some changes made. Considering the unstable period simulation of the mathematical model that ends in 2008-2009, implementation of the model will be made from this year onwards. The prediction period of the mathematical model of the plain was conducted during a period of 2009-2041. Two proposed scenarios (Section 2.3) were implemented and the obtained results were compared in this period of time. During the simulation period, all the recharge and discharge factors that have not been seen in the scenario, have been considered as constant and similar to quantitative simulation in stable conditions. Recharge values from the aquifer surface related to the rainfall are considered constant. The other factors have changed in line with the estimate reported in the scenarios.

Figure 8. Aerial map of Varamin Plain and location of the irrigation canal network.

3.3 RESULTS OF THE FIRST SCENARIO

The most important conditions applied in the first scenario are the non-exploitation of the Mamlou dam during the entire simulation period and the non-implementation of artificial recharge plans (basins 2, 3 and 4). Water transmission through the Varamin canal network to the Varamin irrigation network (Figure 8) is about 2 m^3/s. Also, the amount of water needed for agricultural, drinking and industrial purposes and its supplied sources are similar to the simulation period. Figures 9 and 10 show the situation of groundwater level drop and piezometric level in the years 2021 and 2041 compared to the summer of 2008.

3.4 RESULTS OF THE SECOND SCENARIO

In the second scenario, the assigned values from the discharging of the southeast wastewater treatment plant of Tehran enter the study area and due to the implementation of the Mamlou storage dam, a significant part of Jajrood River surface water resources will not enter the study area (2017). In implementing the model to simulate these conditions, amounts of return water caused by surface water consumption are applied to the model. In this scenario, agricultural, drinking and industry water needs according to predictions have been considered after carrying out the plans. By applying these assumptions, the model was re-implemented to predict quantitative changes of the plain. Figures 11 and 12 show the groundwater level drop in this scenario in unconfined and confined aquifers for two horizons of 2021 and 2041.

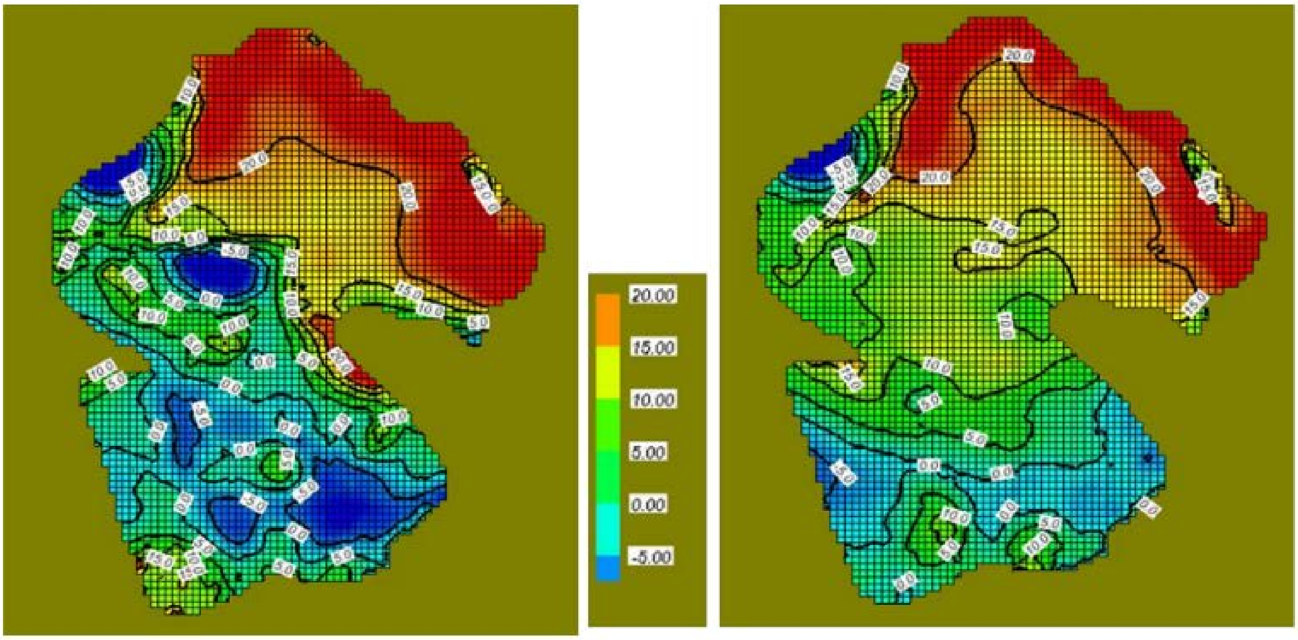

Figure 9. Groundwater level drop in the first scenario in the unconfined aquifer (right) and piezometric level drop in the confined aquifer (left) in the year 2021 compared to the summer of 2008.

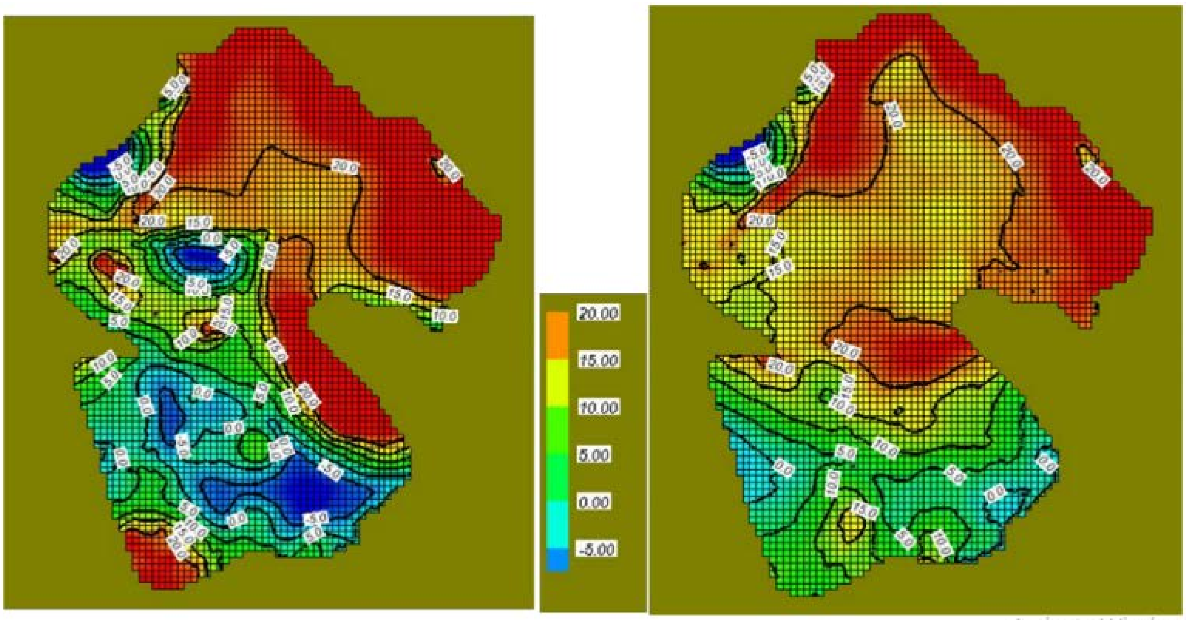

Figure 10: Groundwater level drop in the first scenario in the unconfined aquifer (right) and piezometric level drop in the confined aquifer (left) in the year 2041 compared to the summer of 2008.

In the maps obtained from the first scenario (Figures 9 and 10), situation of groundwater level drop continues as in previous years, but in the second scenario (Figures 11 and 12), considering the utilization of the discharge of the wastewater treatment plant, the groundwater drop rate of the aquifer has decreased, although this decrease continues.

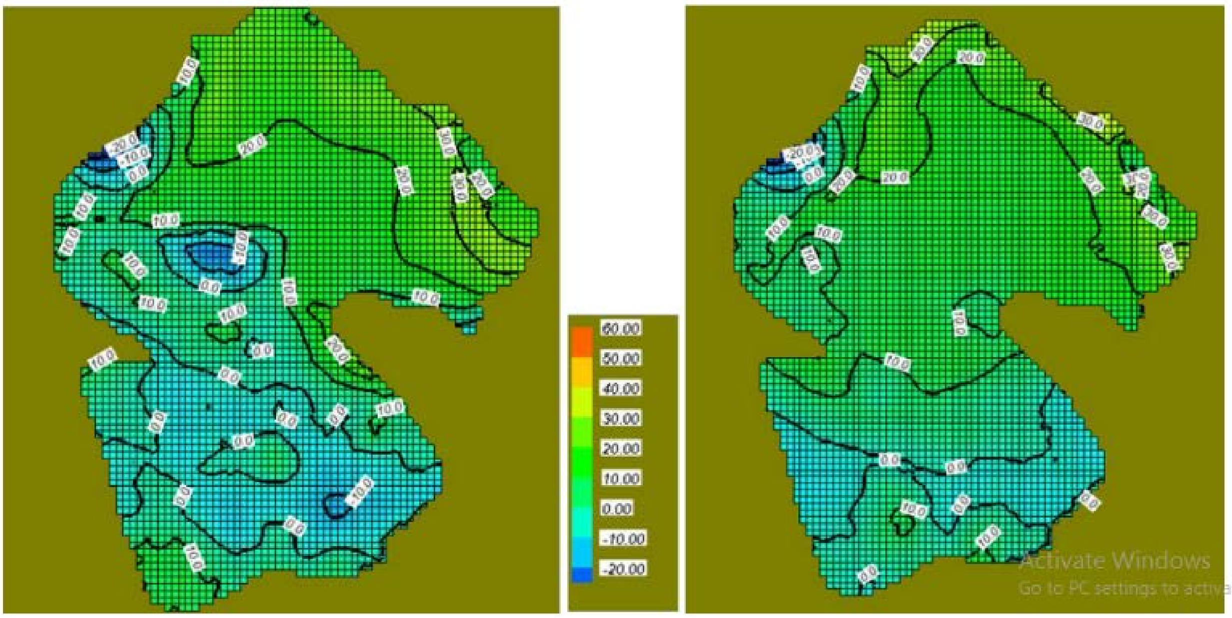

Figure 11: The situation of groundwater level drop in the second scenario in the unconfined aquifer (right) and confined aquifer (left) in 2021.

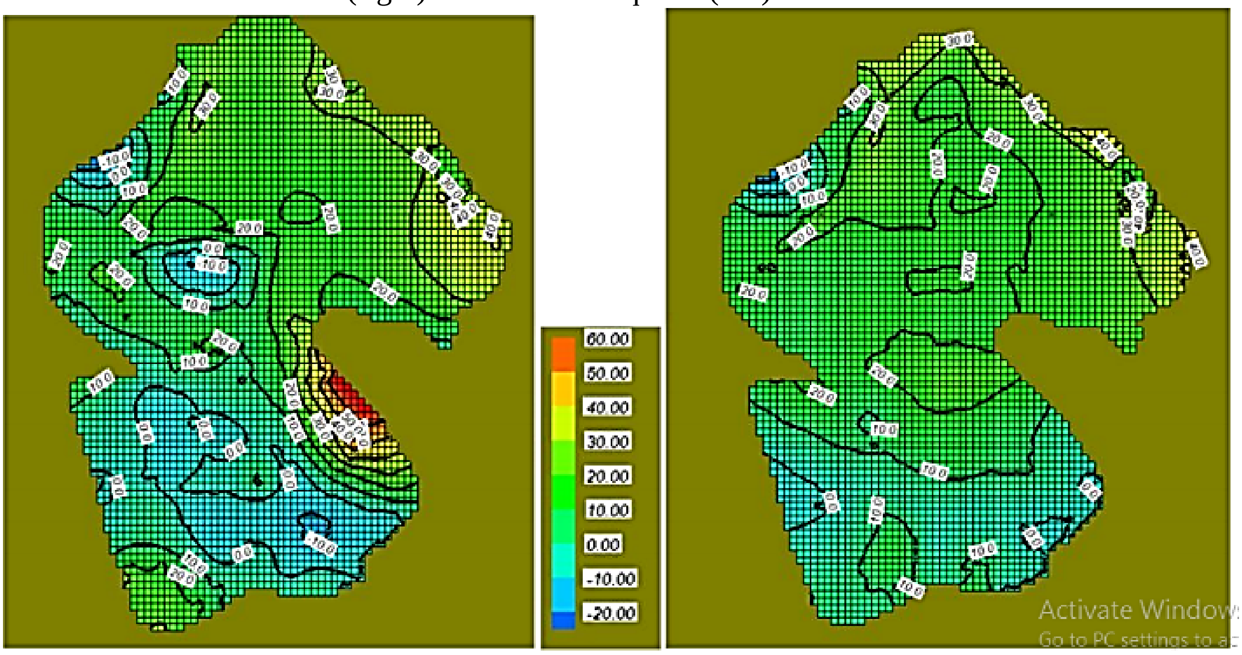

Figure 12: The situation of groundwater level drop in the second scenario in the unconfined aquifer (right) and confined aquifer (left) in 2041.

4. CONCLUSION

In this study, using simulation, the trend of the groundwater level drop has been predicted in two scenarios for future years. As shown in the maps obtained from the model in the first scenario (Figures 9 and 10), the situation of the groundwater level drop continues as in previous years, and the aquifer instability indices are clearly recognizable. The highest drop of the groundwater level is observed in the northern part of Varamin Plain, and as shown in Figure 10, a large part of the aquifer (northern half of the plain) will decline by more than 20 meters in the next 30 years. Under these conditions, the average annual reduction in the reservoir of Varamin aquifer will be 127000000 m^3. In general, in spite of the local uncertainties in the model results, a continuation of the existing conditions will cause the quantitative instability of the aquifer.

As shown in the maps derived from the model in the second scenario (Figures 11 and 12), considering the utilization of the wastewater treatment plant discharge, the aquifer quantitative situation is more appropriate than the present situation (scenario 1). However, the trend of the groundwater level drop continues and the aquifer balance will be decreased. Under these conditions, the highest drop in groundwater level occurs in the northern part of the aquifer. In the southern areas of the plain, due to the existence of the impermeable layer between the unconfined and confined aquifers, the groundwater level of the unconfined aquifer will slightly increase. In the second scenario, due to the supply of Pakdasht's drinking water from the Mamlou dam and in order to remove the drinking water wells, the drop rate of the water table in the south of Pakdasht has slightly decreased.

A comparison of the model implementation in the first and second scenarios shows that with the implementation of planned projects, part of the aquifer's quantitative problems, especially in the northern areas of the plain, will be decreased so that in some areas the groundwater drop (results of the first scenario) has decreased about 30 to 40 meters by 2041. In the second scenario, despite the increase in the water of Tehran wastewater treatment plant and the implementation of the artificial recharge plan, a balance of the groundwater has been decreased with an annual reduction of about 100000000 m^3 in aquifer storage. Therefore, the reduction of water allocation from the Jajrood River to Varamin Plain should be proportional to the increase in water resources from wastewater treatment plant discharge in the south of Tehran. Otherwise, in a short-term period, a significant drop and also land subsidence will undoubtedly occur in the northern areas of the aquifer.

In general, the implementation of recharge and discharge management plans in Varamin aquifer can only lead to a decrease in groundwater level in the aquifer if it does not significantly reduce the percentage of water entering the aquifer. Certainly, the use of current management methods (second scenario) will not have much of an effect on the improvement of the aquifer situation. In addition to the entrance of Tehran treatment plant wastewater into Varamin plain, the plain recharge from Jajrood River should be continued as a suitable natural recharge source.

5. AVAILABILITY OF DATA AND MATERIAL

Relevant information can be made available by contacting the corresponding author.

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