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Forecasting Groundwater Table and Water Budget under Different Drought Scenarios using MODFLOW Model (Case Study: Garbaygan Plain, Fars Province, Iran)

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Abstract

Groundwater drought is a natural hazard that is developed when groundwater systems are affected by drought. When meteorological drought occurs, first groundwater recharge decreases, then groundwater level and groundwater discharge from aquifer decrease. The origin of drought is a deficit in precipitation that takes place in all hydrological cycle elements (flow in rivers, soil moisture and groundwater). Hydrological drought is concerned with the effects of periods of precipitation (including snowfall) shortfalls on surface or subsurface water supply (such as stream flow, reservoir and lake levels, and groundwater). The frequency and severity of hydrological droughts are often defined on a watershed or river basin scale. Although all droughts originate from a deficiency in precipitation, hydrological droughts usually occur with a lag comparing to meteorological and agricultural droughts. It takes longer for precipitation deficiencies to show up in components of the hydrological system such as soil moisture, stream flow, and groundwater. The present research has focused on forecasting the effects of drought on water budget and groundwater table using MODFLOW mathematical model in Garbaygan plain, located in the southeast of Iran. In this study four scenarios including wet year, normal, moderate and severe drought have been considered. Then, using the obtained relationship between precipitation and recharge (natural and artificial) in transient calibration stage, the best estimators have been fit to forecast the recharge. In addition, forecasting water budget illustrated that under different precipitation conditions (from wet year to severe drought), groundwater level will fluctuate so that a larger loss will occur in locations with high densities of wells.

Keywords

Groundwater Drought; MODFLOW; Water Budget; Garbaygan Plain

1. Introduction

As pointed out by the National Drought Mitigation Center (NCDC 2007), drought is a normal, recurrent feature of climate, although many erroneously consider it a rare and random event. It is understandable, however, that every current drought may always be the hardest ever for the people affected by it, since human memory tends to block unpleasant experiences from the past.

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When droughts are of historic proportions, they may trigger major societal changes and forever affect the use and management of water resources (Kresic 2009). Drought is one of the main natural hazards affecting the economy and the environment of large areas of droughts causes crop loss, social alarm degradation and desertification and forest fires. Drought is a complex phenol-menon, which involves different human and natural factors that determine the risk and vulnerability to drought. Although the definition of drought is very complex it is usually related to a long and sustained period in which water availability becomes scarce. Drought can be considered a climatic phenomenon related to an abnormal decrease in precipitation (Serrano and Moreno 2005). Decrease of precipitation is considered as the origin of drought. This results in delayed reduction of runoff and storage like soil moisture or as free water while a more delayed reduction of groundwater flows and reserves is observed. Depending on the choice of the form of water and its related variable of interest, drought is conventionally characterized as meteorological, hydrological or agricultural. Hydrological drought is a significant decrease in the availability of water in all its forms appearing in the land phase of the hydrological cycle. These forms are reflected in various hydrological variables such as streamflow (including snowmelt and spring flow), lake and reservoir level, and groundwater level (Nalbantis and Tsakiris 2009). There are increasing concerns regarding the impacts of anthropogenic actions and extreme droughts on hydrologic systems. The response of groundwater systems to extreme climates such as drought and to anthropogenic actions such as the operation of a dam plays an important role in local hydrological systems (Dai et al. 2010). Groundwater and surface water belong to the same and unique cycle of water. Whenever there is a deficit in rainfall precipitation, a deficit in recharge occurs, the water table is depleted and groundwater discharge through rivers and springs decreases. While this is true, it is not always a climatological drought that triggers a hydrological drought, especially if the groundwater system is considered (Lglesias et al 2009). The area affected by drought is not limited to the river network and its vicinity; it may cover the whole catchment affecting soil moisture content and groundwater levels. For instance, spatial aspects like the area covered are important in land surface modeling, whereas drought severity as measured by a deficit in groundwater may be the key issue in groundwater management. Therefore, different indices may prove equally valuable depending on the area of application. Physically based, distributed hydrological models can be used as a tool to include the spatial coverage in the definition of drought for different variables, like soil moisture and groundwater (Tallaksen et al. 2009). Groundwater response to drought may be asynchronous with other variables. Actually, drought in groundwater systems is mainly analyzed simulating groundwater recharge, discharge and hydraulic heads. Considering in some cases a threshold level approach to define the drought event and evaluating the performance of the systems through performance indicators (Mendicino et al 2008). Many studies have been done by researchers on groundwater drought and its effect on the different sections of hydrological cycle but a few researches have been done on groundwater's water budget. In this field Shahid and Hazarika (2009) investigated groundwater drought in the northwestern districts of Bangladesh. The results showed that groundwater scarcity in 42% area is an every year phenomenon in the region, also analysis of groundwater hydrographs and rainfall time-series reveals that ever-increasing groundwater extraction for irrigation in the dry season and recurrent droughts are the causes of groundwater level drop in the region. Ataie Zadeh and Chitsazan (2009) assessed the impact of meteorological drought on groundwater drought using mathematical model in Meydavud plain in Iran. This study identified that a yearlong drought can decline the water budget from 612 Mm3 to 591/6 Mm3. Also according to S´aenz et al. (2009) drought affects different aquifer types in different ways. Selecting drought indices related to the groundwater systems should be done carefully. Aquifers with a thick unsaturated zone may not be affected by dry conditions at all. On the contrary, karstified shallow aquifers may respond quickly to a drought. In this type of aquifer, a selected piezometer could be a good tool to monitor drought. Yahiaoui et al. (2009) evaluated the frequency of hydrological drought including stream flow and groundwater in Mina catchment in western Algeria. They concluded that as an important random phenomenon in hydrology, the frequency analysis is necessary in the aim to know about the drought's regime. In the Calabria, Italy the groundwater resources were monitored and forecasted by Mendicino et al. (2008). They used a new index namely the Groundwater Resource Index (GRI). The result showed that GRI Index can act as a reliable and useful tool in a multi-analysis approach for monitoring and forecasting drought conditions. As well, Tallaksen et al. (2009) considered temporal and spatial modeling of drought characteristics using the time series include observed rainfall and groundwater recharge, head and discharge simulated by physically based groundwater models in the Pang catchment, UK. They understood that the analysis of the GRI characteristics showed a high spatial variability and, compared to the Z-score through spectral analysis, a significant sensitivity to the lithological characterization of the analyzed region. Furthermore, the GRI shows a very high auto-correlation during summer months, useful for forecasting purposes. This paper focuses on groundwater drought and especially its effects on water table and water budget. In fact, the object of this research is the prediction of drought effects on groundwater level and water budget under different Drought scenarios using MODFLOW model.

2. Materials and Methods

2.1 Description of the Study Area

The Garbaygan plain is situated in the Southeast of Iran. The area of Garbaygan plain is about 83 km^2. Geographically, the area extends from 28° 35´ E to 28° 41´ E latitude and 53 ° 53´ N to 53° 57´ N longitude. In addition, this region is located 190 km far away in the southeast of Fars province center. In fact, this area extends on the alluvial fan where Bishe Zard, as an ephemeral river enters to the plain. The depth of alluvium varies from

19 meters to 58 meters dependent on the position of the alluvial fan. Based on the geographic location the plain height varies so that the highest and lowest elevations are 2066 and 1100 meters above sea level, respectively. According to the alluvial depth and hydraulic conductivity, transmissivity value can change. Therefore, the average of transmissivity and specific yield, which is calculated using pumping tests are 133/8 m^2/day and 10%, respectively. Due to the observed drawdown, a flood-spreading project was set in 1982 with an area about 5.81 km^2. Location of the aquifer and the flood-spreading project has been shown on Fars province and Iran maps in Fig 1. Climatically, there is a hot and dry weather in summer, and also a semi-dry and cool weather in winter in the region. According to De Martonne index, it can be inferred that a semi-dry climate is dominant in the region. The plain receives 289 mm per year precipitation on average. Additionally, the maximum and minimum temperature range from 33.9°C to 6.4°C, respectively. Owing to the high temperature, the average of potential evapotranpiration is about 2934.9 mm per year (Ghahari and Pakparvar 2007). Hydrologicaly, three ephemeral streams cross the aquifer. They have a considerable role in aquifer recharge. Figure 2 represents the status of aquifer hydrology. In the west of the aquifer, only the river of Shur acts as drainage and depletes the aquifer 2 Mm^3 per year (Fatehi-Marj 1994). Geologically there are many formations in this area as well; the region has been folded intensively during Mio-Pliocene Period. The most important formation is Quaternary alluvial (QA) and consists of sand, gravel and silt, which has covered Agha Jary Formation (AJ). This formation is the result of erosion mostly from Agha Jary in upper parts and deposited by rivers or stream in lower part. The Garbaygan plain has been filled with this formation. The Agha Jary formation is one of the widest spread geologic formations in Garbaygan plain, too. It forms the major bedrock on which the alluvium has deposited. Agha Jary is unconformable capped by the Plio-Pleistocene Bakhtyari Formation (BK). Several erosion phases during the Quaternary period has left only small part of scattered patches of the Bakhtiari formation on the Bishe Zard watershed and on small hills in the Garbaygan plain. The Agha Jary formation consists from brown to gray, calcareous, sandstones and low weathering gypsum-veined, red marls and siltstones (Miocene to Pliocene). Underlying formation of Agha Jary is gray marls and sandstones of Razak and Mishan formations that the contact is transitional and conformable. Due to tectonics pressure, a few faults and joints had been created which were observed especially on limestone formations. Figure 3 illustrates some details of geological conditions in this area.

2.2. Precipitation conditions and Aquifer Hydrograph

Groundwater drought can particularly be determined by using recharge and ground-water level (Shahid and Hazarika 2009). Owing to the importance of rain as a main factor in recharging and detecting the drought, variation of precipitation was analyzed from 1992 to 2008 (Figure 4). On the other hand, monitoring of groundwater level is accounted for as the best method to delineate the drought effects on groundwater resources. Therefore, the ground-water hydrograph was drawn with respect to the period by which the precipitation was analyzed (Figure 5).

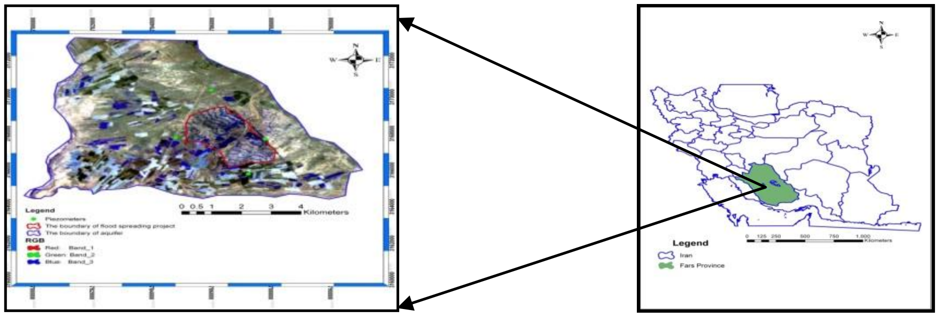

Fig. 1. Geographic condition of the study area

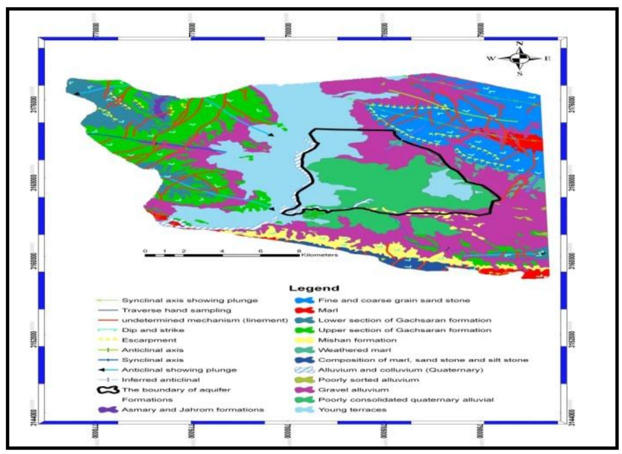

Fig. 2. Geologic condition of the study area

2.3. Groundwater Flow Simulation using MODFLOW

Based on previous studies, MODFLOW model was selected as a useful tool for the object determined. MODFLOW (Modular Three-dimensional Flow Model) is a versatile code to simulate groundwater flow in multi-layer porous aquifers. The model simulates flow in three dimensions using a block-centered finite difference approach. The groundwater flow in the aquifer may be simulated as confined, unconfined or the combination of both. MODFLOW consists of a main program and a number of sub-routines called modules. These modules are grouped into various packages via basic, river, recharge, block centered flow, evapotranperation, well, general head boundaries, drain, strongly implicit procedure (SIP), successive over relaxation (SOR), slice successive over relaxation (SSOR) and preconditioned conjugate gradients (PCG), etc (MacDonald and Harbaugh 1988). In this research the SSOR method has been chosen. Moreover, the rate of allowed iteration and convergence criterion have been appointed as 7000 and 0.001, respectively. According to the above three dimensional analysis condition, transient flow of groundwater can be expressed as the following partial differential function (Equation 1).

$$S\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_x\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_x\frac{\partial h}{\partial y})+W \quad (1)$$

Where K_x, K_y, and K_z are hydraulic conductivities in x, y, and z directions, respectively (m/d); h is water head (m); S is storage coefficient of the aquifer under the water table; and W is sink item (1/d). Combining the initial and boundary conditions, the numeric model was constructed (Wang et al. 2008). Equation (1) describes the groundwater flow under non-equilibrium conditions in a heterogeneous and anisotropic medium provided the principal axes of hydraulic conductivity, which is aligned with the x-y Cartesian co-ordinate axes. Groundwater flow equations together with specification of the flow as well as initial head conditions at the boundaries constitute a mathematical representation of the aquifer system. Numerical methods or electric analog are generally used to solve the groundwater flow equation. Analog methods were in vogue in sixties but mathematical methods had overtaken it during seventies. Advanced numerical methods are in use to solve the partial differential groundwater flow and mass transport equations. Partial derivatives are replaced by the finite difference approximations (Thangarajan 2007).

2.3.1. Model discretization

The study area was discretized into 92 rows and 116 columns using geographical information system (GIS). As the cells were the same regular quadrangular, then in agreement with area of 65 km^2 and considering 100 meters as cell size, the total of 10672 cells were obtained. According to the features of the stratigraphy and pumping test analysis, the aquifer can be considered as one unconfined aquifer. As a whole, the model structure is a matrix of 92 rows, 116 columns and 1 layer.

2.3.2. Initial, boundary and constraint conditions

For reasons of data availability, only 8 points were chosen in 1978 as the initial condition to simulate the groundwater flow, because the recharge and discharge conditions of the aquifer were natural in this year (Fatehi-Marj 2000). According to some performed studies, two types of boundary conditions were determined. Most of the areas were specified a no flow boundary (Neumann conditions). Therefore, derivatives of the head (flux) across the boundary are set to zero. This type of boundary has been used in the southern, eastern and northern boundary where the Agha Jary formation exists and no flow can be originated from these areas. For the western boundary because of Shur s' river, dependent head boundary (Cauchy Conditions) was used. Thereby, the derivatives of the piezometric head were constant and did not change with time. The model user specifies this head across the specified boundary (Mohamed et al 2005).

2.3.3. Model Calibration and Verification

As mentioned, the aquifer condition in April 1978 was assumed as the initial condition for the steady state model calibration. The model could not be initiated at an early date due to the non-availability of water level data before April 1978. Minimizing the difference between the computed and the field water level values for each observation point, the steady state model calibration was started. Trial and error method was used for calibrating than other optimization methods such as PEST or UCODE (Anderson and Woessner 1992). After calibration, error rates were evaluated using root mean square error (RMSE) and coefficient of determination (R2). In order to perform model calibration and very-fication, total recorded precipitation periods during 40 years were analyzed, then every year was separated to wet and dry periods. In fact, each period was considered as one stress period; afterwards each month was identified as a time step, too. Due to piezometric wells data that were established in 1992 and groundwater level, which has been measured until 2008, 33 stress periods were obtained. Two-thirds (22 stress periods) of total stress periods (from 1992 May to 2003 April) were assigned for transient calibration and one third (11 stress periods) from 2003 May to 2008 November were allocated for model verification. Similarly, RMSE and R2 were used for evaluating the rate of errors.

2.4. Prediction of Groundwater level and Water Budget

To study the groundwater behavior due to drought on the aquifer, the verified model was used to evaluate different options under drought conditions. To achieve this purpose four scenarios including (1) wet year condition, (2) normal condition, (3) mode-rate drought condition, and (4) severe drought condition were considered. For this goal, Standardized Precipitation Index (SPI) as a valid index for determining the meteorological drought (MacKee et al. 1993) was calculated in 12 months time-scale. In this research, preci-pitation under 4 options was computed by solving SPI index (Eq. (2)) as the following equation:

$$Pi = (SPI \times SD) + \overline{P} \qquad (2)$$

Where p_i is the rate of precipitation under desired condition, SPI represents drought condition, SD is standard deviation during long period (40 years) and $\overline{P}$ is the average of precipitation during the time that precipitation has been recorded (40 years). Afterwards, the relationship between preci-pitation and recharge in calibrated periods was studied. Due to the effects of meteoric infiltration and artificial recharge on the aquifer recharge, their relationship with precipitation was completely separated. To understand the precipitation condition effects on water budget, the relationship between SPI index and water budget was determined, too. Finally, meteoric and artificial recharge rates under different scenarios were obtained and then entered to MODFLOW model and water table and water budget were predicted with the consideration of fixed exploitation.

3. Results

First, the recorded precipitation in the rain gauge station of Baba Arab, where is the nearest station to the aquifer, was used to demonstrate rain conditions during 17 years. According to rain data, which is illustrated in the Figure 4, there are numerous variations during these years so that the difference between the maximum and minimum (range) is about 450 mm. Also, the rainfall during 12 years was less than the average. In the subsequent step, to assess groundwater level during 17 years, the hydrograph of aquifer was drawn as shown in Fig. 5. Based on the graph, water table raised from March 1992 to November 1996 but after this period, it has droped until now. In 1996, groundwater level reached the maximum value, which it was calculated about 1147 meters above mean sea level.

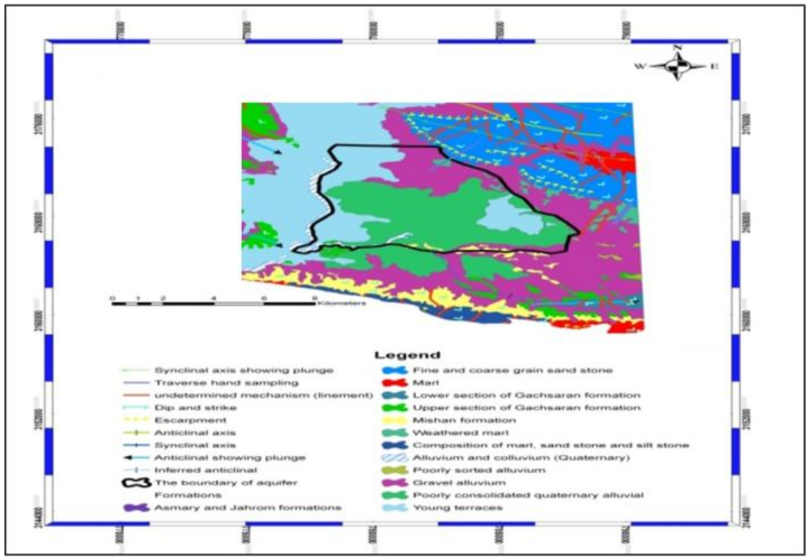

Fig. 3.Geology map of the Garebaygan plain

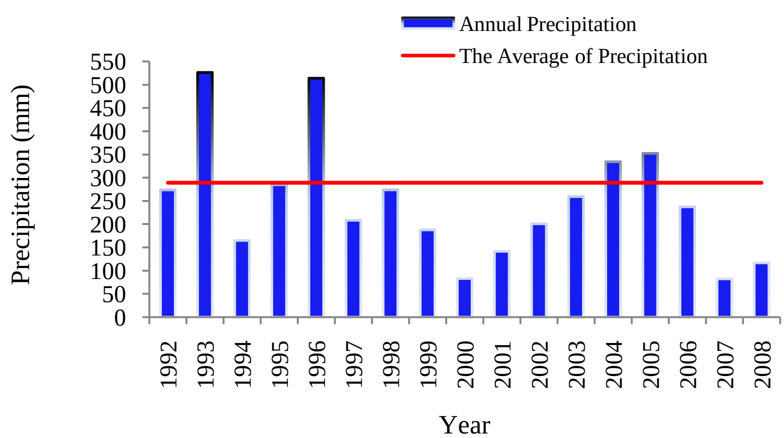

Fig 4. Oscillations of precipitation from 1992 to 2008 in Baba Arab station, near the Garbaygan plain

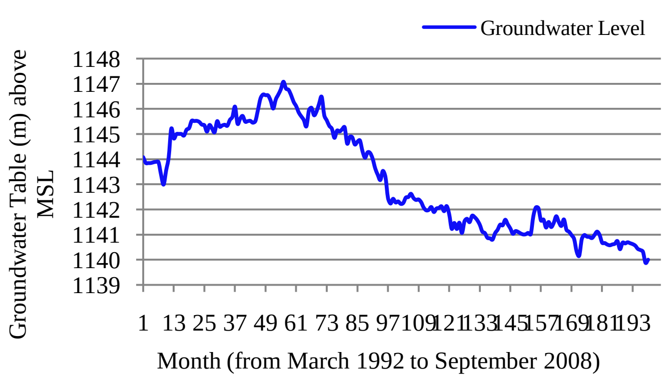

Fig. 5. The hydrograph of aquifer drawn using four piezometers established in the Garbaygan aquifer

As it was mentioned, calibration was done using trial and error method and was continued until good agreement between observed and simulated groundwater levels was achieved. Moreover, it was performed for four existed piezometers and the results are illustrated in Figure 6. In addition the verification was done using the rest of data. In this way, the model was run and although no change was applied to the variables error rate was low. Analysis of the bias rate shows that RMSE varies from 0.458 to 0.923, as well as R2 ranges from 0.568 to 0.957. Similarly, there is a high accuracy in verification step as RMSE varies from 0.301 to 0.567 and R2 ranges from 0.628 to 0.946. According to Figure 7, there is a good agreement between simulated and observed groundwater levels in four piezometers, too.

Afterwards, to understand the precipitation effects on water budget, the relationship between SPI index and water budget was determined and is plotted in Figure 8.

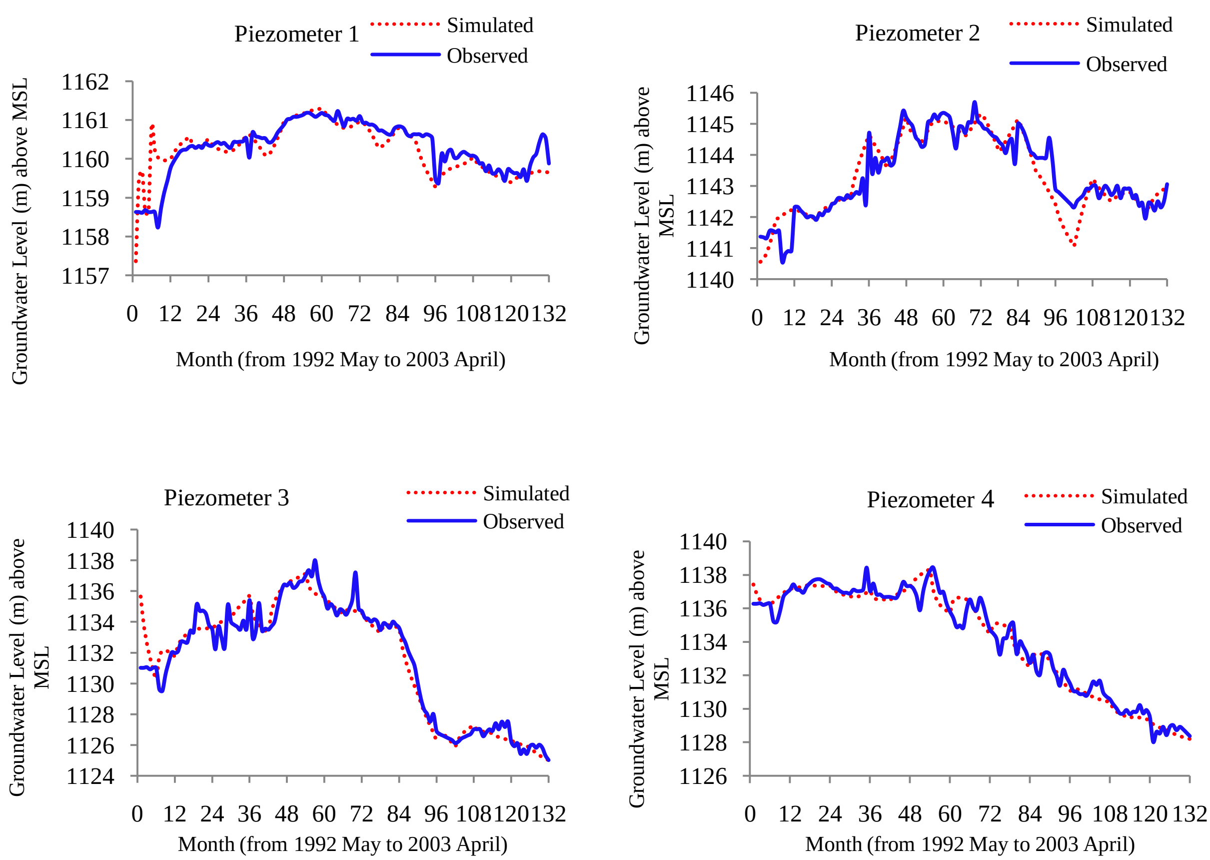

Fig. 6. Comparison of the observed and simulated groundwater levels in transient state for four piezometers

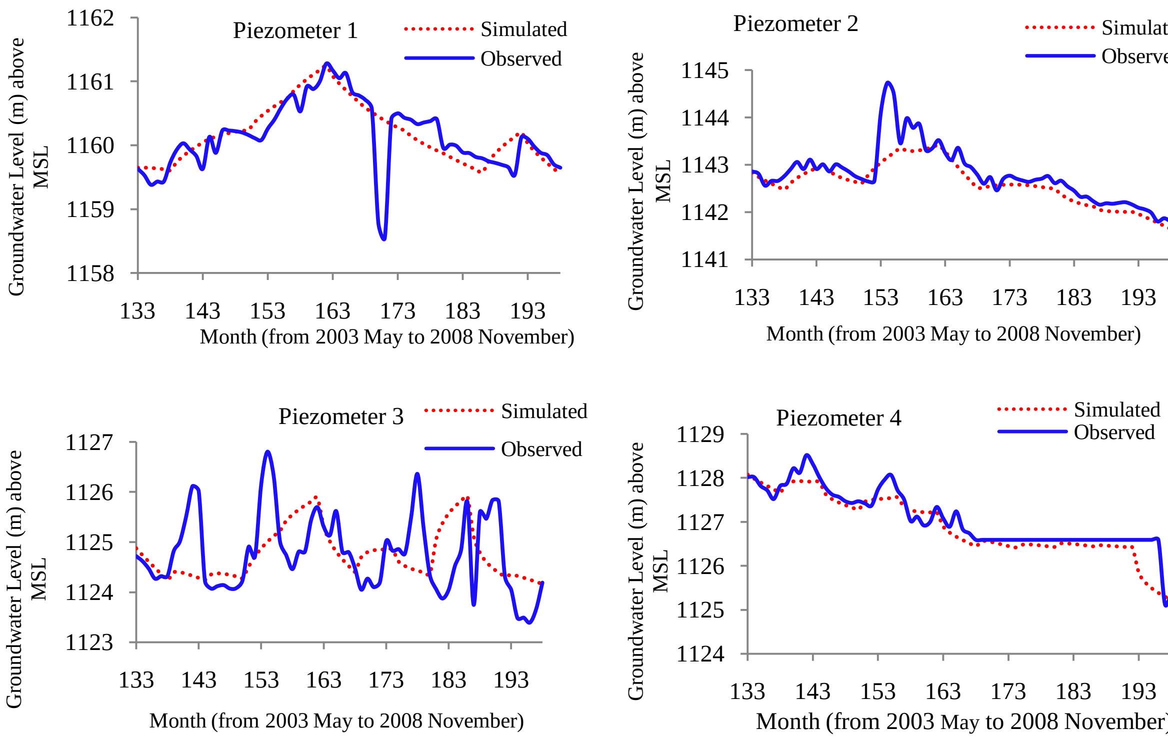

Fig. 7. The comparison of observed and simulated groundwater level in verification step

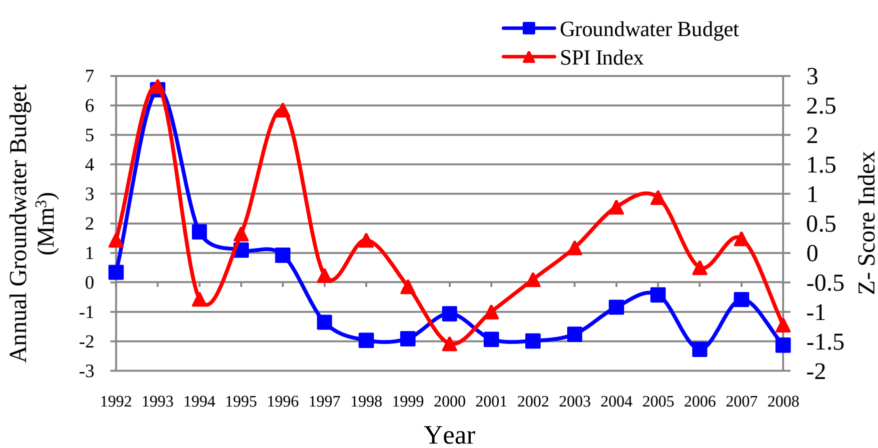

Fig. 8. Variations of SPI Index and groundwater budget computed using MODFLOW model

Based on Figure 8, it can be concluded that the precipitation affected groundwater con-siderably as the fluctuations of SPI index and groundwater budget are very close to each other. The best equation that show the relationship between SPI index and water budget is a cubic model with the R^2 about 0.651 (Eq. 3).

$$y = -0.986 - 0.075x + 0.036x^2 + 0.272x^3 \qquad (3)$$

Where y is water budget rate (Mm3), and x is the SPI index. To determine the recharge, including meteoric infiltration and artificial recharge, the relationship between preci-pitation and recharge (meteoric infiltration and artificial recharge) was investigated separately.

Then, each model that could better fit was selected. Finally, linear regression equations were selected as the best models. Therefore, Equation (4) and Equation (5) describe the relation between precipitation and natural and the artificial recharge, respectively.

$$y = -6.293 \times 10^{-8} + 2.763 \times 10^{-7} x \quad (4)$$

$$y = 0.0643 + 1.524 \times 10^{-5} x \quad (5)$$

Where y indicates the amount of recharge (Mm3) in each model cell and X is the total precipitation (mm) in every year. Afterwards, recharge was obtained under every drought scenario and then entered to the model so that the results were demonstrated using the graph of water budget (Figure 9) and groundwater contours (Figure 10).

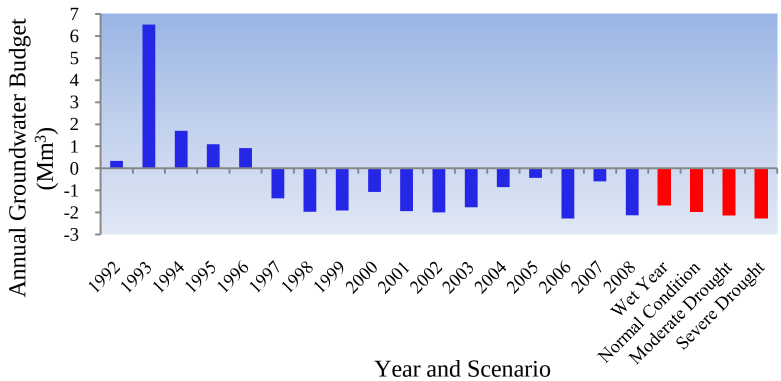

Fig. 9. The annual groundwater budget from 1992 to 2008 and under different drought scenarios

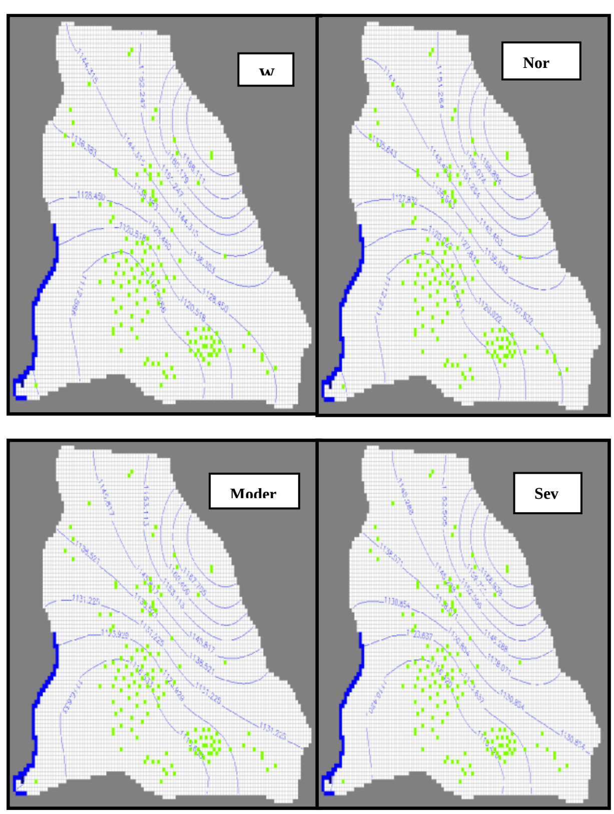

Fig. 10. Prediction of groundwater contours for four drought scenarios in the Garbaygan aquifer

According to Figure 7 it is concluded that water budget was positive until 1996, as in 1993 by flood spreading the aquifer storage reached to more than 6 Mm3, although from 1997 it was decreased and in 2006, the maximum aquifer shortage has become about -2/27 Mm3. Generally, groundwater budget dramatically has been affected by the precipitation rate. Additionally, prediction of groundwater level illustrates that there are maximum and minimum of groundwater contours in wet year and severe drought, respectively. Of course, these fluctuations are variable over different locations of the aquifer.

4. Discussion and Conclusions

Since, precipitation is the most important source for replenishing the aquifer in this region, so water table fluctuations are dependent upon the rain, too. Analysis of the hydrograph shows that after establishing the water spreading system, first groundwater level raised. But, since November 1996 it has droped until now. In spite of the wet years (2004 and 2005), water table was dropping, so the significant factors creating this problem can be inferred. According to Fatehi- Marj (2000), after uplifting the groundwater level by which the water spreading project has been induced, numerous wells have been installed by the farmers so that today about 86 wells exist. Whereas there were only about 20 wells before implementing the artificial recharge project in the region. Extending farmland areas, developing of irrigation projects as well as growing demand led to an imbalance between recharge and exploitation of the groundwater resources. Therefore, the trend of the hydrograph is declining due to overexploitation. It is illustrated in Figure 6 that there were 10 drought events from 1996 to 2008, hence overexploitation was not able to withdraw water table exclusively. As Bachmat (1999), Shaban (2009) and Shahid and Hazarika (2009) emphasized, ground-water withdrawal is not only due to drought but also related to overexploitation of groundwater resources, it can be inferred that groundwater drought in this region is significantly human-induced drought and is better to call it as a groundwater scarcity (Shahid and Hazarika 2009). Many studies have proved that there is usually a lag between different kinds of droughts especially between climatological and hydrological droughts. The precipitation effects on groundwater level in each aquifer are dramatically variable so that the response of an aquifer to drought is strongly dependent on the type of aquifer, hydraulic parameters (transmissivity, storage and specific yield) recharge, depth of the saturated zone, flow paths and size of the aquifer. Aquifers with thick, deep unsaturated zones and large catchments are not affected by short drought periods, or even if the aquifer response is subdued and delayed in time. This fact gives groundwater an opportunity as a source of fresh water during periods of scarcity and has conditioned the fact that the more valuable crops are irrigated frequently with groundwater or in mixed systems (Llamas 2004). Owing to the small area of aquifer (65 Km^2), and that the high hydraulic parameters also being limited to the depth of saturated zone a low lag exists between climatological and groundwater drought in this aquifer. Based on Figure 8 it can be concluded that there is a good agreement between SPI index, as an indicator of precipitation, and the groundwater budget. Similarly, the results of imposing different scenarios in MODFLOW model showed that under various rain conditions, groundwater budget will be negative. Although, depending on the kind of scenario used, this negative values will be more or less comparing to the last year. According to the results, if wet year occurs, water budget will be less negative compared to the last year (2008); similarly if drought conditions (moderate and severe drought) occur, the groundwater budget will be more negative than wet year condition. Therefore, it can be inferred that the exploitation had a more important role than drought on groundwater fluctuations. Therefore, groundwater management must be applied to the exploitation rate in Garbaygan aquifer. Similarly, due to the high potential of flood in the Bishe Zard watershed upland, it will be a good suggestion to do more detail investigations to establish other artificial recharge projects. Based on the predictions of the groundwater table, the most withdraws will occur in the locations with high density of wells. On the contrary, the least withdrawal will be observed in the areas that are more affected by water spreading projects than other areas.

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