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Application of groundwater modeling to predict drought impacts on groundwater resources in the Garbaygan plain, Iran

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Abstract

This study investigates the application of groundwater modeling for the understanding how meteorological droughts propagate through the groundwater system and how the latter responds in terms of storage and water levels. The study region is the Garbaygan plain, located in the southeastern area of Iran, where the farmlands are strongly dependent on irrigation by groundwater. Four meteorological drought scenarios, as defined by the standard Z-score index, the latter being computed based on precipitation data between 1993 and 2008, are considered, namely, a very wet situation, a normal, a moderate and a severe drought. Afterwards, a numerical groundwater model is set up, calibrated and validated on observed groundwater heads during that time period to estimate the groundwater storage and levels, wherefore the unknown aquifer recharge has then been one of the calibration targets. The latter is then used to set up a linear regression model between precipitation and recharge. The results indicate that even under very wet and normal years, as defined by the corresponding annual Z-scores, the groundwater budget will still be negative (Over draft), which means that other factors, such as the increasing - and not well-known - groundwater over-exploitation may also be the origin of a groundwater drought. Finally, groundwater budgets and levels for the “future” year 2009 have been predicted for the four drought scenarios, using corresponding Z-score- estimated annual rainfall in the regression equation to compute firstly the recharge and then using the latter to drive the groundwater flow model.

Keywords: groundwater drought, groundwater modeling, MODFLOW, Garbayagan plain, Iran

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1. Introduction

Drought is a complex phenomenon, 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 during which water availability becomes scarce. Drought can be considered a climatic phenomenon related to an abnormal decrease in precipitation [1]. So, a decrease of precipitation is considered as the origin of drought. This results in a delayed reduction of runoff and storage as soil moisture or as free water, and eventually in an even more delayed reduction of groundwater flows and reserves. Depending on the choice of the form of water and its related variables of interest, drought is conventionally characterized as meteorological, hydrological or agricultural [2]. A hydrological drought leads to a significant decrease of the availability of water in the land phase of the hydrological cycle, e.g. streamflow (including snowmelt and spring flow), lake and reservoir levels, and groundwater levels.

Physically based, distributed hydrological models can be used as a tool to simulate the effects of drought on variables, like soil moisture and groundwater [3]. Groundwater response to a drought has a lag compared with other hydrological variables. Drought in groundwater systems is mainly analyzed by simulating groundwater recharge, discharge and hydraulic heads in response to a drought event, and the reaction of the system is evaluated by performance indicators [4].

Many studies have been done to date on groundwater droughts and their effects on the different sections of hydrological cycle, but only a few studies have been carried out with a focus on the groundwater's water budget. Also, hydrologists have attempted to provide a better understanding of groundwater droughts in terms of how meteorological drivers and, in particular droughts propagate through hydrological systems [3, 5 - 7]. To that regard, Panda *et al.* [8] have carried out a study to detect and quantify how he groundwater level fluctuate in the state Orissa (India) to figure out the combination impacts of droughts and anthropogenic pressure by means of the non-parametric Mann–Kendall statistical procedure. For that purpose, the pre- and post-monsoon groundwater table historical records measured in 1002 observation wells during the period 1994–2003 were investigated. The findings indicated that the groundwater dropping as a result of rainfall reduction below the long-term average rainfall during dry years, high temperatures, and man-made pressure have not been even compensated through the recharge in wet years. Shahid and Hazarika [9] investigated

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groundwater droughts in the northwestern districts of Bangladesh. Their results showed that groundwater scarcity is an every-year phenomenon in about 42% of the area the region, triggered also be the ever-increasing groundwater extraction for irrigation in the dry season and recurrent droughts which are the causes of the groundwater level drops in the region.

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 meteorological drought. In this type of aquifer, piezometers are a good tool to monitor the drought.

Whereas hydrological droughts, i.e. streamflow droughts, have been greatly taken into consideration in the literature, groundwater drought analyses have not yet been gaining such popularity, though the studies of Mendicino *et al.* [4], Yahiaoui *et al.* [10], Tallaksen *et al.* [3], Fiorillo and Guadagno [11, 12], Jang *et al.* [13] are noteworthy in this regard.

Since 1983 the water spreading project has operated in the application area, i.e. Garbaygan aquifer, it was expected that a good buffer/protection against drought conditions has been provided. Although, in initial years the groundwater head had been increasing due to considerable amount of artificial recharge has been occurring, at the same time drilling new utilization wells all over the aquifer has been significantly augmented and as a result the positive impacts of the water spreading project have been neutralized by increasing the utilization wells from 20 to more than 80. More importantly, since drought is accounted for a recurrent phenomenon in Iran as a semi- arid region and owing to strong dependent of different sectors including agricultural, human and industry on the groundwater resources in this area, therefore, to propose an effective drought risk management plan for such an area, not only drought monitoring is required but also forecasting the impacts of drought should be taken into consideration. Above all, based on many studies conducted on drought in all over the world and also in Iran, they have mainly focused on monitoring and forecasting of meteorological droughts and as such groundwater drought monitoring and forecasting particularly using groundwater flow modeling have been rarely dealt with. Thus, based on our best knowledge, no reference study is available till day on applying groundwater flow modeling suing MODFLOW to forecast the groundwater drought. Therefore, in this paper, as the main objective of this research, the propagation of meteorological drought under natural situations through the groundwater system and forecasting of groundwater storage under different drought severities will be considered by constructing the groundwater flow model and analyzing historical data record of precipitation and groundwater level over the aquifer. The groundwater catchment where these analyses will be done is Garbaygan aquifer which is a plain located in Fars province, Iran. [14].

2. Materials and methods

2.1 Study area

The Garbaygan plain is situated in the southeast of Iran and covers an area of about 83 km^2. Geographically, the area extends from 28° 35′ E to 28° 41′ E latitude and from 53° 53′ N to 53° 57′ N longitude (see Figure 1). Geologically, this plain extends on an alluvial fan, where the major Bishe Zard and two other ephemeral streams enter the Garbaygan plain. Because of this ephemeral-stream system, surface-groundwater interactions play a considerable role in the area [15]. The thickness of the alluvium varies from 19 to 58 meters, so that the transmissivity, though the hydraulic conductivity of the alluvium may be more or less constant – varies spatially throughout the aquifer.

Pumping tests performed in different parts of the aquifer, resulted in an average transmissivity and specific yield of 133.8 m^2/day and 0.1, respectively. Because of the strong dependency of the (mostly irrigated) agriculture and domestic water users in the region on the groundwater resources which has led to considerable groundwater drawdowns in the area, a groundwater recharge/flood-spreading system, covering an area of 5.82 km^2, was set up in 1983 (see left panel of Figure 2). Many different geological formations can be found in this area, as it has been folded intensively during the Miocene-Pliocene period. The most important formation is the Quaternary alluvial (QA) which consists of sand, gravel and silt. Underneath lies the Agha Jary formation (AJ) which is the result of erosion mostly from Agha Jary in upper parts and deposited by rivers or streams in its lower part. Most of the Garbaygan plain is filled with this Agha Jary formation which consists of brown to gray, calcareous, sandstones and low weathering gypsum-veined, red marls and siltstones (Miocene to Pliocene). The formation underlying the Agha Jary consists of gray marls and sandstones of Razak and Mishan formations. Due to tectonic forces, a few faults and joints had been created, especially in the limestone formations. Figure 2 illustrates some details of geological conditions in this area.

The prevailing climate of the Garbaygan plain is of semi-arid type, with a perennial mean precipitation of 289 mm, wherefore the largest portion (80%) falls during fall and winter and only 20% in spring and summer. The maximum and minimum temperatures in the study region change from 33.9°C to 6.4°C, respectively. The high maximum temperatures, in conjunction with arid conditions, necessarily, result also in a high amount of potential evapotranspiration of 2935 mm per year [16].

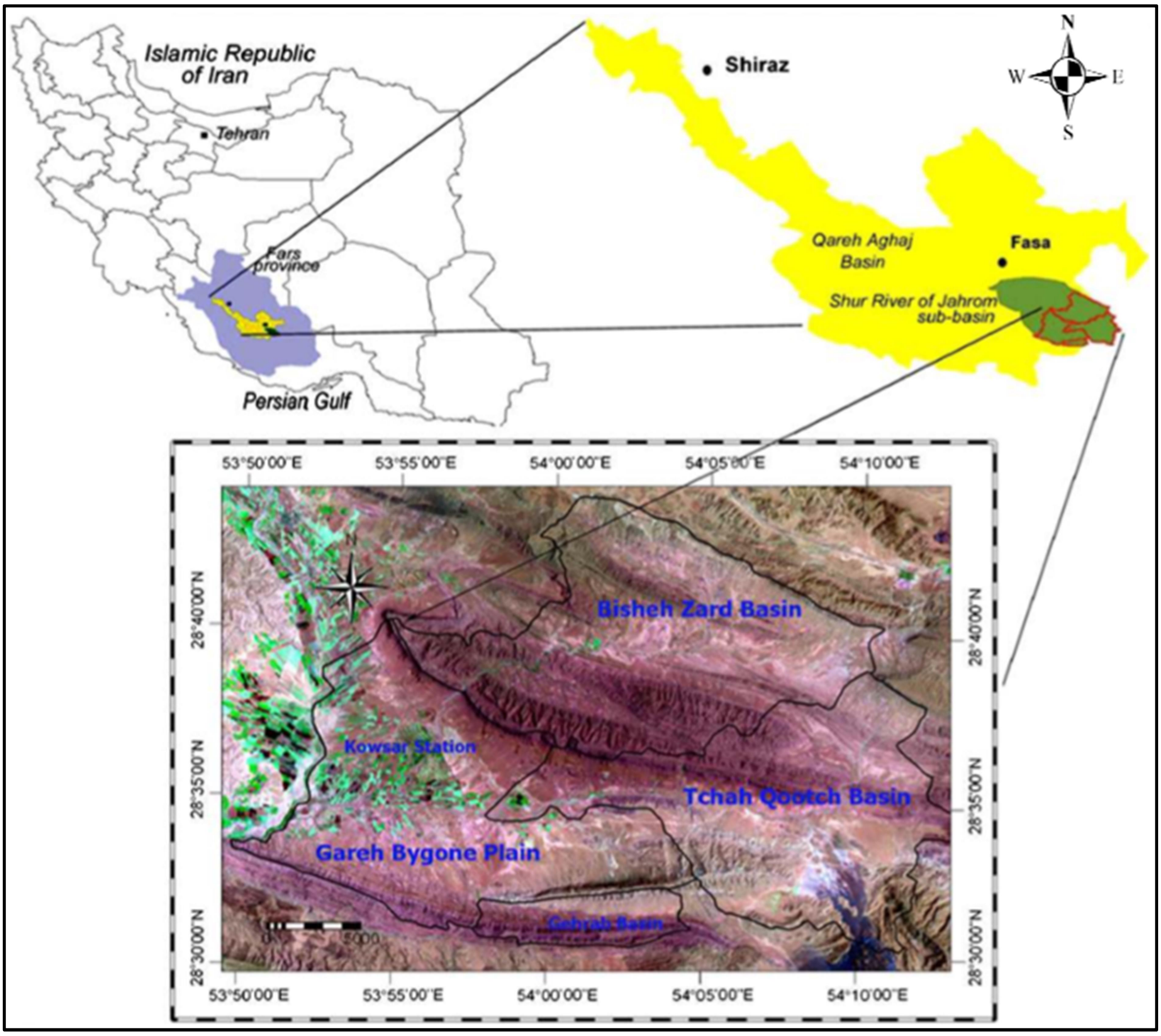

Figure 1 Location of the Garbaygan plain, Iran, with aquifer area in green [16]

2.2 Rainfall and groundwater level data

Groundwater level hydrographs are often the most important source of information about the hydrogeological conditions of aquifers. The hydrograph pattern is governed by physical characteristics of the groundwater flow system, the rainfall pattern driving recharge, the interrelation between recharge to and discharge from an aquifer [17], but not to the least, by other management options, such as extraction, irrigation and land use changes [18, 19].

A propagating meteorological drought through a groundwater system, known as groundwater drought, is also detectable by means of such a groundwater hydrograph, even though it is difficult to distinguish whether a groundwater level drop is not also due to over- abstraction [9].

To understand how groundwater levels fluctuate in response to the precipitation, the monthly groundwater table, based on a geospatial average of four piezometers across the region, has been plotted, together with the annual rainfall for 16 hydrological years beginning in October, 1992 and ending in September, 2008 in Figure 3. One can clearly notice from the figure a systematic decrease of the groundwater table since 1997, after the rainfall had started to decrease in that year. However, although the rainfall began to increase again in 2000, the groundwater levels continued to drop. This would mean that the possible increased rainfall recharge of the aquifer after that time is not enough to make up for ongoing groundwater depletion by augmented pumping in the first decade of the 20th century.

2.3 Groundwater modeling

1) The MODFLOW groundwater model

In this study, the groundwater system is simulated numerically by means of the well-known MODFLOW groundwater flow model [14]. This model simulates groundwater flow in a multi-layer aquifer system in three dimensions using a block-centered finite difference approach, wherefore aquifer

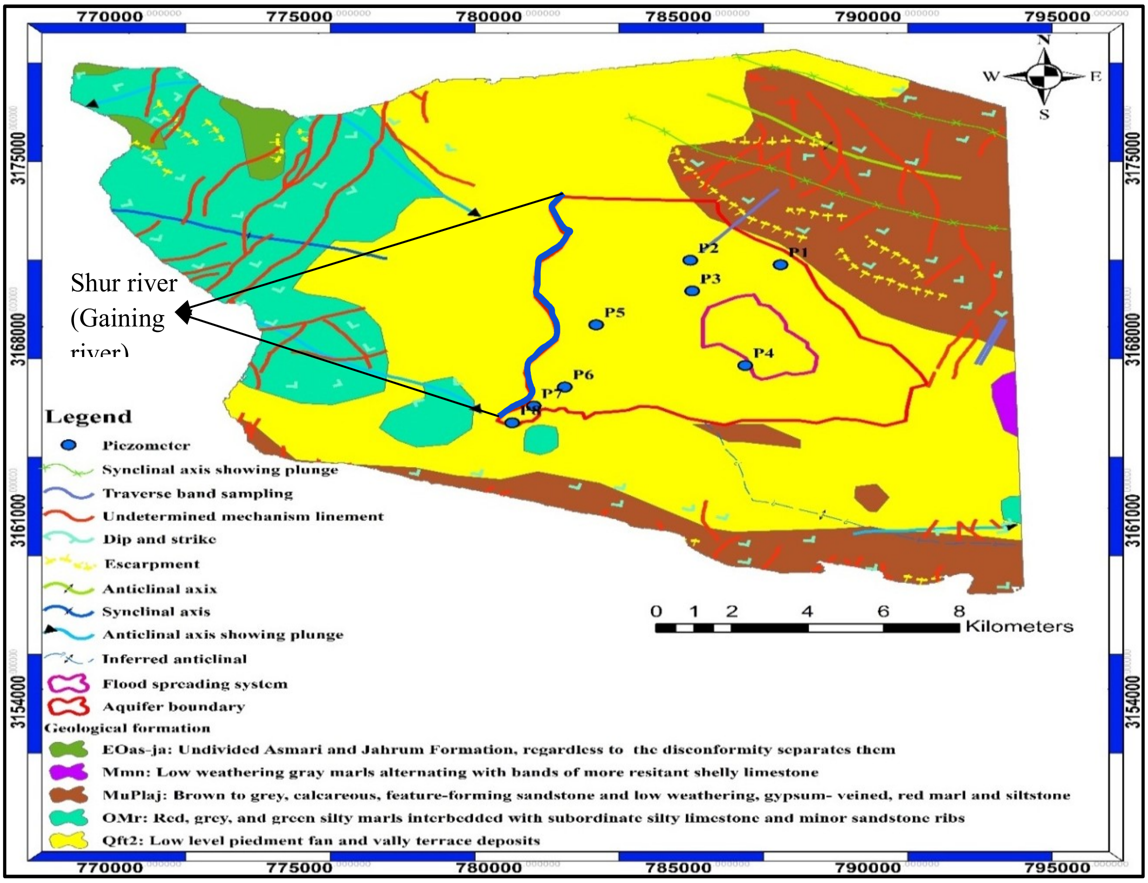

Figure 2 Geological map and the boundary condition of the aquifer (red: Neumann (no-flow)- condition; blue: Cauchy BC) and location of the water spreading project

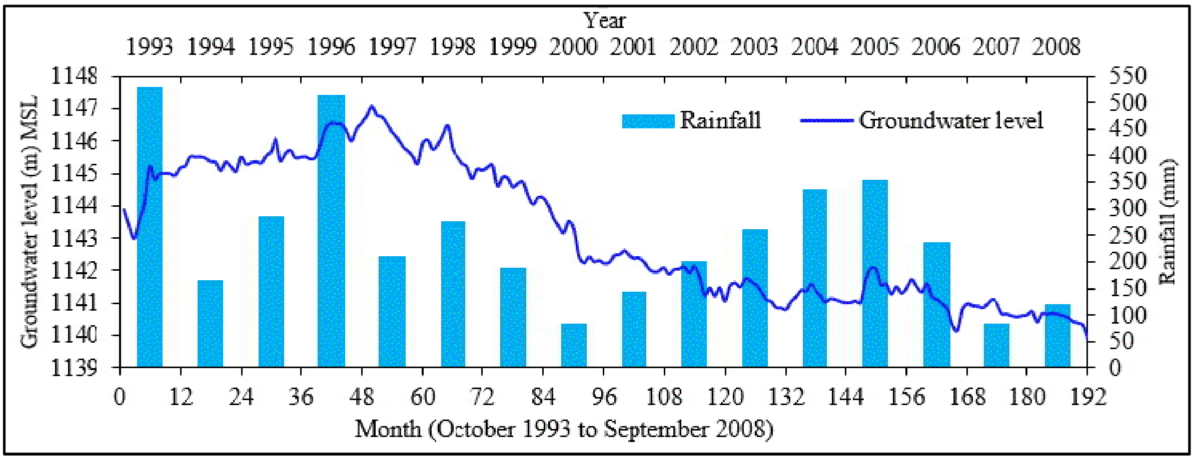

Figure 3 Fluctuations of the groundwater levels along with the annual rainfall variability

layers may be assumed to be confined, unconfined or a combination of the two. MODFLOW consists of a main program and a number of sub-routines called modules. These modules are activated to simulate specific features of the groundwater flow system, and are known as packages, e.g. the basic, block centered flow, recharge, evapotranspiration, wells, general head boundaries, river, drain, etc. In addition, various numerical solution techniques are available, such as the strongly implicit procedure (SIP), successive over relaxation (SOR), slice successive over relaxation (SSOR) and the preconditioned conjugate gradient (PCG) [4, 14, 20]. Here the well-proven SSOR-method is used.

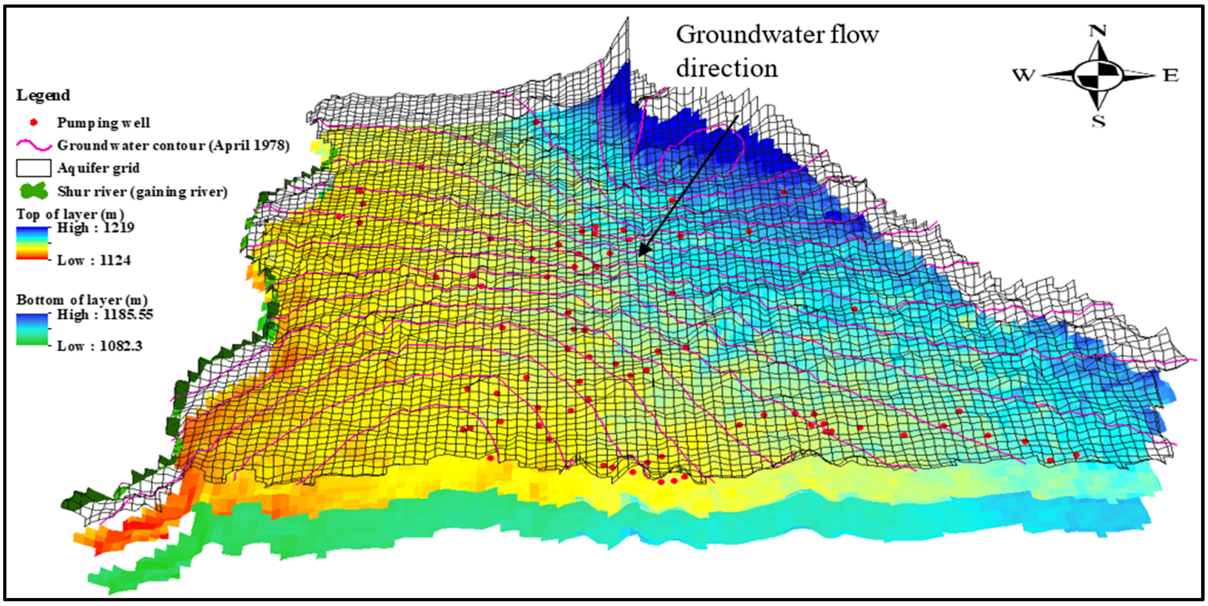

Figure 4 Conceptual model of the aquifer containing spatial discretization, the top and bottom of layers, the hydraulic boundary (Shur river) and dominant groundwater flow direction

The partial differential equation solved by MODFLOW is the three-dimensional groundwater flow equation.

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

where h is water head [m]; K_x, K_y, K_z are the hydraulic conductivities [m/d] in x, y, z-directions, assuming that the coordinate system has been orientated in the direction of the principal axes of the conductivity ellipsoid; S is the storage coefficient of the aquifer and which depends on whether the aquifer layer is confined or unconfined; and W is a source/ sink term [1/d].

The groundwater flow equation (1), together with a specification of boundary- and initial head conditions at the model domain's boundaries, constitutes – at least theoretically – a unique mathematical representation of the aquifer system [21].

2) MODFLOW- model setup

For the MODFLOW- model setup, a one-layer unconfined aquifer in the study area is assumed which is discretized horizontally into 92 rows and 116 columns, i.e. a total of 10872 cells, with the aid of a geographical information system (GIS), the use of which is now very common in applied groundwater modeling [22]. The cells are quadratic with a size of 100 m x 100 m. As initial conditions head measurements from 8 piezometers in 1978 are used, as in that year the recharge and discharge conditions of the aquifer could still be considered natural (Figure 4) [15]. According to other studies that have been done in the present study region, two types of boundary conditions (BC) are used (See Figure 2), namely, Neumann no-flow BC's in the southern, eastern and northern boundaries, which touch the rather impervious Agha Jary formation. At the western boundary - west of the Shur river -, which touches a swampy marsh area with a relatively stable water-holding capacity, a head-dependent (Cauchy) BC is used, wherefore the driving head in the marsh is set to a constant, so that the swamp- groundwater flow-exchange adjusts accordingly, depending on the computed head in the aquifer [23].

3) Model calibration and validation

The main purpose of the calibration step is to simulate the observed data as best as possible by adjusting the important hydraulic variables which characterize the groundwater system. These calibration parameters are the hydraulic conductivity, the specific yield (effective porosity) and the natural recharge of the aquifer. The model was initially calibrated for steady-state conditions, using 8 observation points including 4 contact springs (In such springs from where the groundwater comes out can be considered as the groundwater head) and 4 piezometers measured in April 1978 as calibration targets, as it can be expected that the recharge and discharge of the aquifer system at that time were still natural, given that the flood spreading groundwater recharge system was only constructed in 1983. The few known values of hydraulic conductivity and recharge were adjusted to find the best fit between simulated and measured heads at the 8 piezometers which are more or less evenly distributed across the aquifer.

The model was subsequently calibrated for transient conditions, wherefore the specific yield is adjusted accordingly in order to mimic observed head variations in the 4 piezometers. As the historical 40-year record of the rainfall indicates a clear distinction of wet and dry periods in a year, each year was also divided into two stress periods, namely, for the 6-month

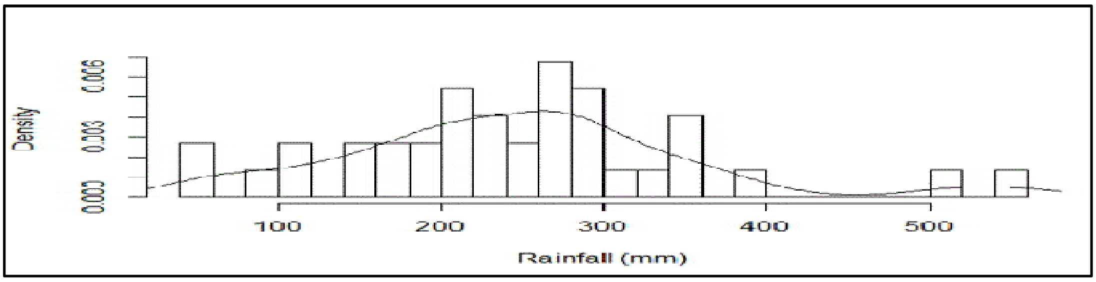

Figure 5 Empirical density histogram of the observed rainfall with fitted density kernel

Table 1 Drought classification scale by means of the Z-Score values

Category	Extremely Wet	Very Wet	Moderately wet	Near normal	Moderately dry	Severely dry	Extremely dry
Z-Score	> 2.00	1.50 to 1.99	1.00 to 1.49	-0.99 to 0.99	-1.00 to -1.49	-1.50 to -1.99	< -2.00
Value used	……	1.745	……	0	-1.245	-1.745	……

wet period which lasts from December to May, and a 6-month dry period lasting from June to November.

With the transient groundwater head observations available between May, 1992 and November, 2008 (see Figure 1), 33 stress periods were generated, out of which the first two third were used for the transient calibration, (May, 1992 to April, 2003), and the remainder (May, 2003 to November, 2008) served for the validation of the model [24].

4) Prediction of groundwater levels and Z-score drought analysis

To predict how the groundwater system reacts in response to external stresses like a meteorological drought, which is defined by the deficit of the rainfall amount in a given time period, compared with the average historical rainfall (taken over at least 30 years), the validated groundwater model was applied to predict the groundwater levels and storage under different drought conditions, as defined by a meteorological drought index.

For the definition of and meteorological drought index the commonly used Z-Score CZ_i [25] is considered. Assuming that the precipitation data follows a Pearson Type III distribution the Z-Score does not require adjusting the data by fitting the data to the Gamma or Pearson Type III distributions. Because of this, it is speculated that Z-Score might not represent the shorter time scales as well as the SPI. The CZi for a particular month i is calculated by means of the Wilson–Hilferty cube-root transformation of this distribution as:

$$CZ_i = \frac{6}{C_s}\left(\frac{C_s}{2}\Phi_i + 1\right)^{\frac{1}{3}} - \left(\frac{6}{C_s}\right) + \left(\frac{C_s}{\sigma}\right) \quad (2)$$

where CZ_i is an index indicating drought severity, 6 is the standardized deviation of the precipitation for the time series being considered for drought monitoring (Monthly, seasonally, annually, and so on), Cs is the skewness coefficient of probability density function (PDF) which is calculated using Eq. 3 and Φ_i is the same as z-scores which are expressed in terms of standard deviations (6) from their means ($\bar{P}$) calculated on basis of time series of precipitation being considered for the study (P_i), i.e. monthly, seasonally, annually, and so on (Eq. 4).

$$C_s = \frac{\sum_{i=1}^{n}(P_i - \bar{P})^3}{n * \sigma} \quad (3)$$

where n shows the number of observation data in the time series of precipitation (Monthly, seasonally, annually, and so on).

$$\Phi_i = \frac{(P_i - \bar{P})}{\sigma} \quad (4)$$

By solving Eq. (4) for P_i, amount of precipitation for each of scenarios (Table 1) and in each time scale (Monthly, seasonally, annually, and so on) can be computed through the following formula:

$$P_i = (\Phi_i * \sigma) + \bar{P} \quad (5)$$

Figure 5 shows the empirical density histogram of the observed monthly rainfall data. One may notice clearly that the rainfall distribution differs much from a classical normal distribution, as it extends much to both extremes of the data range. Thus, the assumption of an extreme-value distribution, such as the Pearson III above, and, with it, the Z-score approach, appears to be warranted.

Table 1 lists the 7 classes of the standard drought classification. starting from "extremely wet" and ending at "extremely dry". As these two extreme class members, occur only very infrequently, i.e. have very long return periods, they are not considered further in the subsequent analysis. Furthermore, a "moderately wet" class is left out, in order to better define distinguished separate classes with the available rainfall data and, similarly, of the MODFLOW-simulated groundwater levels and storage. Consequently only 4 drought classes are considered in the Z-score- analysis. To calculate the monthly precipitation corresponding to each scenario, firstly the mean of each drought class is computed which leads to a specific value making it possible to compare and to contrast all the other scenarios in the same situation and to define the upper and lower truncation levels of each scenario class in a clear way. Afterwards, using (Eq. 5), with Φ now denoting the Z-score- value, the corresponding real precipitation limits are estimated for each drought scenario category of Table 1.

2.4 Rainfall-recharge relationship

As the study aquifer is recharged by (1) the diffuse recharge as a direct natural recharge by the rainfall and (2) artificial recharge induced by the floods entering the water spreading recharge project, two separate linear regression models are developed between the rainfall (explanatory variable) and the named two recharge processes (response variable) in the transient calibration and validation simulations steps, namely,

$$R_{nat} = -6.293 * 10^{-8} + 2.763 * 10^{-7} * P \quad (6)$$

$$R_{art} = 0.0643 + 1.524 * 10^{-5} * P \quad (7)$$

where R_{nat} and R_{art} denote the natural and artificial recharge rate (m/day), respectively, and P (mm/T_{stress}) is the amount of the rainfall in the stress period T_{stress} of six months length. The regression equations (6) and (7) result in coefficients of determination of R^2 =0.76 and 0.65 respectively, i.e. good relationships between the rainfall and natural and artificial recharge are obtained.

Subsequently, the precipitations calculated by Eq. 5 for each of the drought condition scenarios are imported into these regression models to compute the corresponding recharge rates which are then used further as inputs into MODFLOW, to predict the ensuing groundwater levels and storage under these scenarios.

3. Results

3.1 Observed rainfall and groundwater level changes

From the plot of the variations of the precipitation along with the fluctuations of the groundwater levels over the 16 hydrological years (Figure 3) and from an average 289 mm/year annual rainfall - calculated on the basis of a 40 years historical record, one can conclude that the rainfall amounts were normal or exceeded this average for only 4 years. Nevertheless, the groundwater table has been dropping since November 1996, even though it has increased before from March 1992 through October 1996, as a result of the installation of the artificial recharge project at that time and also after rainfall increased again between 2001 and 2005. Hence, it can be inferred that the groundwater levels are not only controlled by the diffuse natural recharge, but also by other factors, like the groundwater over- abstraction rate which is not well known here. Thus the positive impacts of artificial recharge and increased diffuse recharge during the wet years have been largely offset by increased groundwater over- exploitations.

3.2 MODFLOW-simulations of the groundwater levels

The results of the steady state and transient solutions of MODFLOW-calibration and validation l are plotted in Figures 6, 7 and 8 respectively. These figures indicate a good fit of the simulated heads against the observed heads in 8 observation points for the steady state solution in April 1978 and the same is true for the transient calibration in the modelled area, with an average RMSE of 0.70 and 0.43 m and of the coefficient of determination R^2 varying from 0.57 to 0.96 and 0.63 to 0.95 for the calibration- and validation periods, respectively. Therefore, the results of the groundwater simulations can, overall, be considered as satisfactory, although in some months desirable calibration and validation fits were not achieved. This can mainly be explained by two major uncertainties, namely, firstly, to the many unregistered agriculture wells whose pumping data is not available and, secondly, the amount of artificial recharger entering the aquifer during periods of unrecorded floods that have occurred in the wake of storm events.

3.3 Groundwater budget variation as a function of the Z-Score index

To have a better idea about how the groundwater budget components have been changing over the time and, more importantly, to detect the time when the deficit, i.e. negative budget has been started, the simulated groundwater components including all discharging and recharging factors are listed in Table 2. One can clearly notice that the overall budget became negative from year 1997 on and never reversed again since that time.

To understand how the groundwater budget responds to the annual precipitation variability, meteorological droughts defined by the Z-Score index are plotted parallel with the MODFLOW simulated groundwater budget variation (MMC) (Figure 9). From this figure, one may notice that the groundwater budget follows well the drought index and this finding is supported by a rather good R^2 = 0.65 obtained for the following cubic polynomial regression model between the Z-score index and the water budget WB.

$$WB = -0.986 - 0.075 * Zscore + 0.036 * Zscore^2 + 0.272 * Zscore^3 \quad (8)$$

3.4 Groundwater recharge prediction

As explained, by using the Z-scores for the precipitation under the four considered drought scenarios (Table 1) in Eq. 5, the corresponding rainfall amounts are estimated which then are used in the two regression models (Eqs. 6 and 7) established in the transient calibration and validation MODFLOW simulations, to predict the natural and artificial recharge rates. These are then imported into the model to predict the corresponding annual groundwater levels and budgets. The results are presented in Figure 9 which shows,

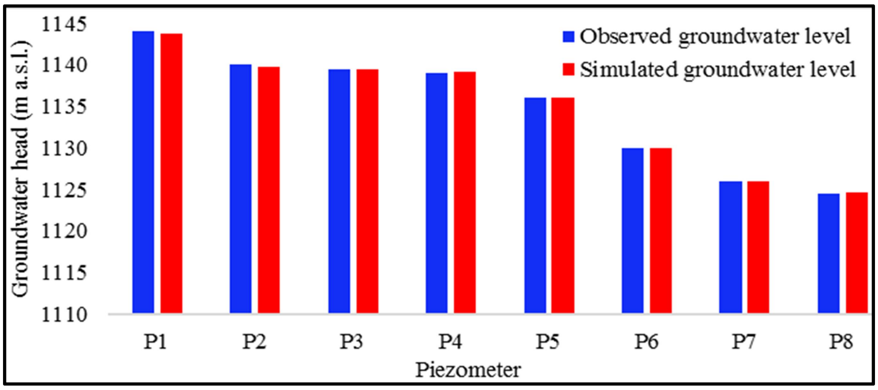

Figure 6 Observed and simulated Groundwater levels for steady state solution in April 1978

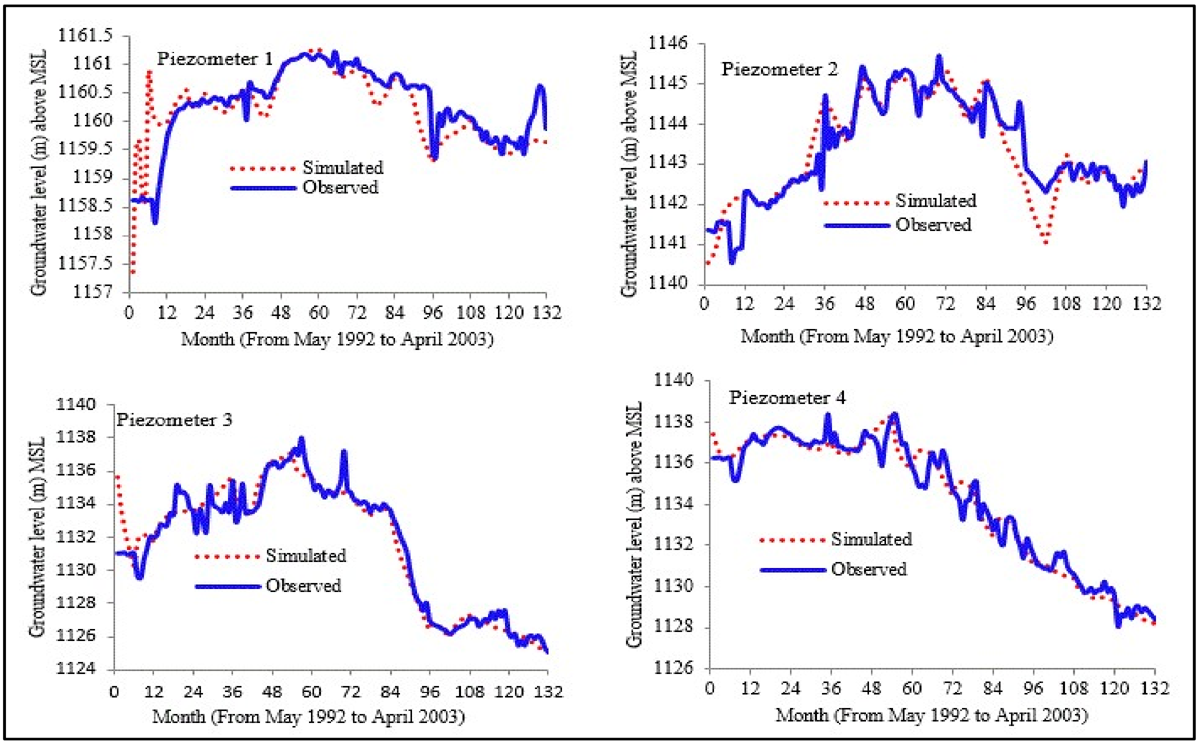

Figure 7 Comparison of observed and simulated groundwater levels in the transient calibration step

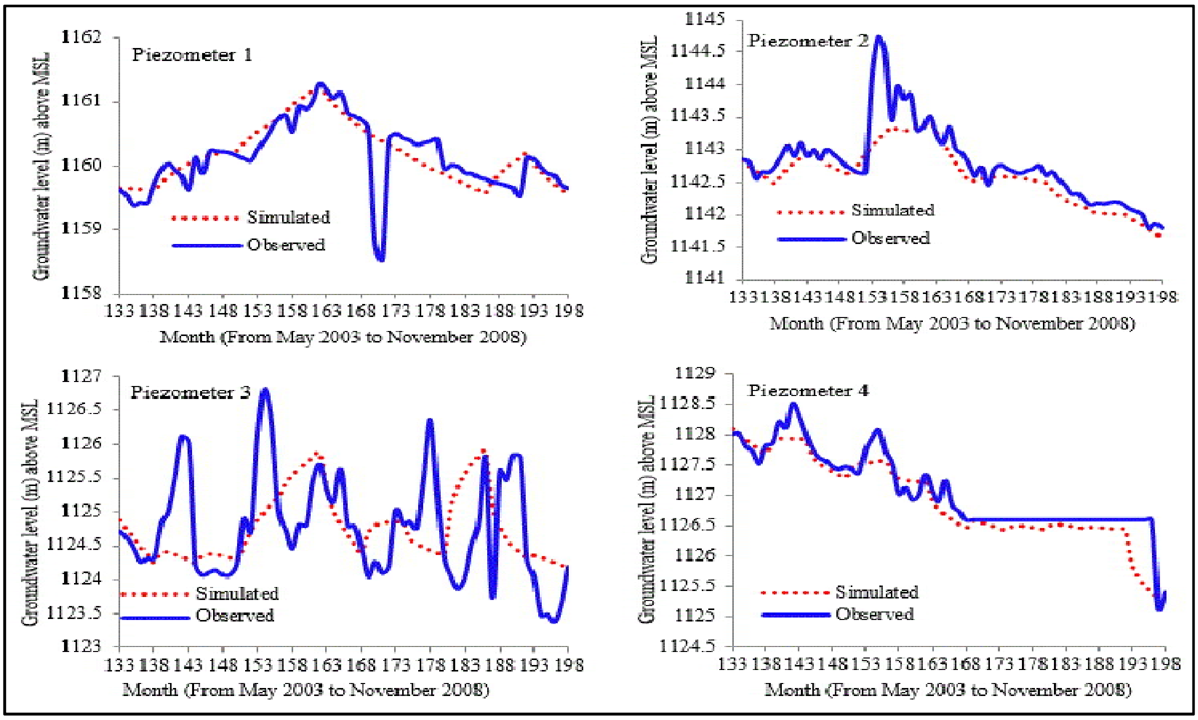

Figure 8 Comparison of observed and simulated groundwater level in the transient validation step

Table 2 Annual groundwater budget components and the overall balance as simulated by MODFLOW

Year	Natural recharge (MCM)	Artificial recharge (MCM)	Recharge from river network (MCM)	Discharge from river network (MCM)	Discharge from pumping wells (MCM)	Overall groundwater budget (MCM)
1993	18.53	0.10	43.03	-5.25	-32.03	24.37
1994	16.12	1.29	37.25	-4.89	-32.04	17.73
1995	16.06	0.50	37.13	-5.01	-35.53	13.14
1996	13.17	0.87	30.44	-5.81	-37.22	1.45
1997	13.76	1.58	31.79	-6.60	-45.45	-4.91
1998	15.69	0.62	36.26	-5.52	-56.11	-9.04
1999	15.54	0.82	35.91	-2.70	-65.63	-16.05
2000	13.89	0.57	32.12	-0.95	-73.35	-27.70
2001	19.90	1.10	46.00	-0.32	-75.05	-8.03
2002	17.94	0.42	41.46	-0.22	-72.94	-13.34
2003	19.44	0.60	44.92	-0.18	-75.97	-11.18
2004	21.94	0.77	50.71	-0.14	-79.79	-6.50
2005	22.28	1.02	51.50	-0.13	-74.76	-0.91
2006	21.00	0.93	48.53	-0.12	-76.19	-5.72
2007	19.52	0.71	45.11	-0.12	-77.24	-12.01
2008	21.30	0.97	49.22	-0.12	-77.55	-6.17

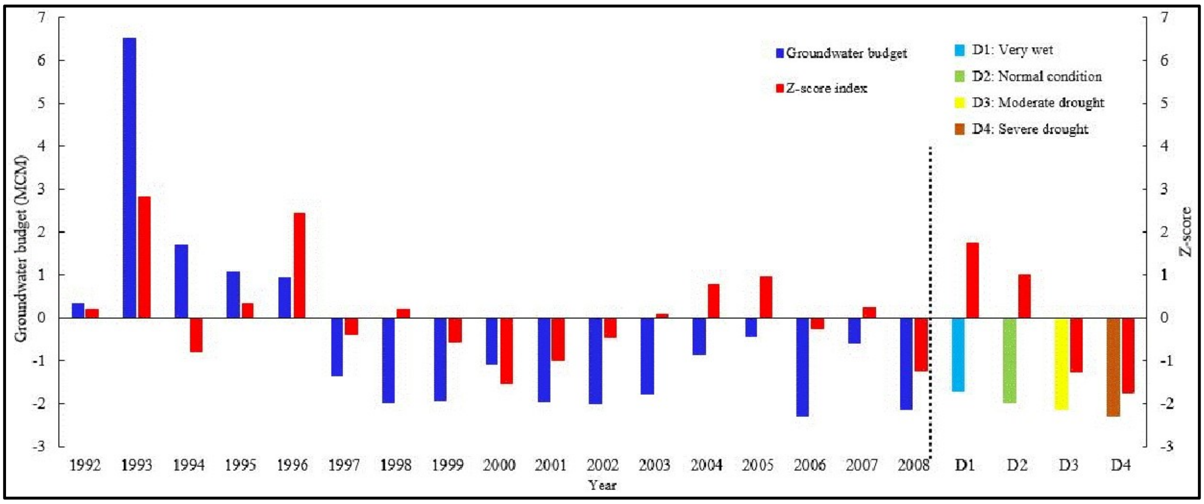

Figure 9 Variations of the Z-score index and of the simulated groundwater budget over time, with the four colored bars on the right of the vertical dashed line representing water budgets (deficits) predicted for year 2009 which resulted from four drought severities (D1=very wet, D2=normal, D3=moderate drought and D4=severe drought), assuming one of the four associated drought scenarios of Table 1

somewhat expectedly, the more or less correlated course of the average annual Z-score and the groundwater budget. Strangely enough, the water budget is even not positive, i.e. a surplus is experienced, when enough rainfall, like in a very wet year (defined by the corresponding average Z- score- index of Table 1) is received. Indeed, it is evident that the groundwater budget was positive from 1992 until 1996, with the highest amount of 6.5 Mm^3 obtained, due to some large floods diverted into the water spreading project in 1993. However, the water budget has been continuously decreasing since 1997 and it did not even return to a stable, equilibrated state during the 2004 and 2005 water years which had high rainfall amounts (Figure 3) and, based on the average annual Z-scores during those years (Figure 9), are accounted for as wet years. The MODFLOW-simulations have then been extended by one year beyond the end of the observation time period 2008, to simulate how a particular "future" drought scenario (out of four, as indicated in Table 1) would affect the groundwater budget further in this subsequent year (2009). The results are plotted right of the vertical dashed line of Figure 9 and they indicate clearly that even under a most benevolent D1=very wet -2009-year scenario, a negative groundwater budget is obtained. The situation gets worse for the other three, drier scenarios D2, D3 and D4.

4. Discussion and conclusions

The analysis of the groundwater levels shows that after the installation of the groundwater recharge spreading system, these have been rising until October 1996, after which they have been dropping more or less monotonously. Generally speaking, in small aquifers made of sediments with rather high hydraulic conductivities, such as the Garbaygan aquifer, it is expected that groundwater should be influenced within a few months after strong rainfalls have been received. However, our data indicates that this is not the case here, as large precipitation amounts occurring during the very wet years 2004 and 2005 were not able to alter the groundwater level positively. In fact, the groundwater utilizations recorded annually by the Fars province water authority state that the number of groundwater wells used for agricultural irrigation had dramatically increased from only 20 wells before the set- up of the water spreading project to more than 86 wells in recent years, not even counting the many unregistered wells [15]. As Shahid and Hazarika [9], Fatehi Marj and Taie Semiromi [24] have emphasized, the observed groundwater level drops in the study region are not only due to droughts, but also due to an ongoing overexploitation of groundwater resources there, which means that the groundwater droughts experienced here are mainly human-induced.

Many studies proved that there is usually a lag time between a meteorological and a hydrological drought. The precipitations effects on groundwater levels in each aquifer are greatly variable, as the response of an aquifer to drought is strongly dependent on the type of aquifer, its hydraulic parameters (transmissivity, storage and specific yield), recharge, thickness of the saturated zone, flow paths and the size of the aquifer. Thus, aquifers with thick, deep unsaturated zones and large catchments are not affected much by short drought periods, e.g. [4, 9], so that the aquifer may still act as a source of fresh water during periods of scarcity. However, in the present case study, given the rather small size of the aquifer (65 km^2), with high values of the hydraulic conductivity, short lag times between the meteorologically-induced infiltration and the groundwater table fluctuations are experienced. Moreover, in some water years, no direct relationships between the drought index computed from the rainfall amounts and the groundwater budget could be seen. For example, for the very wet year 1996, the high-intensity precipitation (Figure 3) may have generating more runoff and so less effective infiltration so that the groundwater table did not react as one would expect.

The MODFLOW-simulations predict that regardless of which of the four precipitation/drought scenarios is considered, the groundwater budget is still always negative and this holds even for very benevolent "very wet" year conditions. Therefore, the conclusion can be made that, in addition to the hydrological drought situation, the groundwater exploitation plays also a key role in the groundwater level drops. Thus, an appropriate groundwater management plan should be provided to effectively limit the groundwater utilization in the Garbaygan aquifer. In this regard, two practical and efficient methods are recommended. One would be to change the traditional irrigation system which is known to be poorly efficient as large parts of the pumped water are evaporated in this hot and arid region, and the other would be to set up other potential artificial recharge projects which, in turn, could be an economical method to also alleviate the negative impacts of the frequently occurring floods in this watershed.

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