Iranian Journal of Science & Technology, Transaction B, Engineering, Vol. 31, No. B5, pp 509-521
Printed in The Islamic Republic of Iran, 2007

STUDY OF GROUNDWATER RECHARGE IN THE VICINITY OF TASHK LAKE AREA*

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Abstract– Due to decreasing precipitation in recent years, lack of perennial surface water resources, and the high volume of groundwater extraction in the vicinity of Tashk Lake (called Tavabe-e-Arsanjan), the groundwater level decreases, and as a result, salt water from Tashk Lake intrudes into the fresh groundwater coastal aquifers. Several technical countermeasures are used to prevent or retard the groundwater salinization process. One of them is to increase (artificial) recharge in upland areas to enlarge the outflow of fresh groundwater through the coastal aquifer, and thus, to reduce the length of the salt water wedge.

In this research, the natural recharge of groundwater is studied using the Cumulative Rainfall Departure (CRD) method with regards to the existing information in the study area. This study focuses on using both revised CRD (R-CRD) and CRD methods to simulate, and consequently predict, transient water table fluctuations. A user-friendly program named GREM, which is written in Visual Basic language, is used to minimize the difference between simulated and observed water table elevations. The simulated water table exhibits good agreement with the observed water table (modeling efficiency = 0.933). The percentage of the cumulative rainfall departure (r), which results in a recharge from precipitation, is estimated to be 33.6. This implies that less than half of the precipitation acts to recharge the water table. The results showed that the natural recharge is not enough to compensate the high volume of groundwater extraction in the study area. The end objective of this study is to provide the foundation for the construction of a regional model of the Tavabe-e-Arsanjan groundwater basin to enable sustained agricultural production while mitigating the impact of salt water intrusion.

Keywords– Groundwater recharge, CRD method, salt water intrusion, Tavabe-e-Arsenjan

1. INTRODUCTION

The demand for groundwater is increasing due to the rise of world population and economic growth. One of the major factors that limits the extraction of groundwater from coastal aquifers is the threat of salt water intrusion. There have been many case histories in different parts of the world where over-pumping has caused the intrusion of sea water or salt water, thereby ruining the aquifers. With the increasing extraction of groundwater in coastal zones, water level decreases and salt water intrusion phenomenon happens. The increasing demand for groundwater has raised concerns about resource sustainability and has highlighted the need for reliable estimates of groundwater recharge.

Many papers related to groundwater recharge have been published. Wu *et al*. used numerical simulations to study the relationships between rainfall and recharge by infiltration at different groundwater depths [21]. The timing and magnitude of recharge determined by a soil moisture balance approach and groundwater flow modeling was studied by Taylor and Howard [19]. Xu and Tonder used a revised CRD (Cumulative Rainfall Departure) method to estimate recharge [22]. Chapman and Malone compared different models for the estimation of groundwater recharge [8]. Taniguchi estimated the past groundwater recharge rates from deep borehole temperature data [18]. Mkwizu focused on balancing groundwater recharge and abstraction rates as a mechanism of ensuring the sustainability of groundwater use [13].

*Received by the editors May 23, 2005; final revised form December 9, 2006.
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In recent years, in arid and semi-arid regions such as Iran, the water level has declined by reducing recharge due to low precipitation and, increasing the rate of extraction of groundwater [1]. Coastal aquifers around the two jointed Bakhtegan and Tashk evaporation lakes in the northeast of Fars Province of Iran are good examples of salt water intruded aquifers due to the over pumping of water for irrigation purposes. Many of the farmers from the villages located in these coastal lands were forced to abandon their farms due to the salinization of irrigation water wells, especially in the western part of Tashk Lake called hereafter Tavabe- e- Arsanjan.

Several technical countermeasures can be used to prevent or retard the salinization process. One of them is to increase the (artificial) recharge in upland areas to enlarge the outflow of fresh groundwater through the coastal aquifer, and thus, to reduce the length of the saltwater wedge [15].

The objective of this research was the construction and calibration of both the CRD and the revised CRD (R-CRD) models to simulate the response of the water table due to transient precipitation events. The focus of the calibration effort was then to simulate water table elevation data using both models. The outcome of this calibration effort was to estimate the fraction of precipitation which acts to recharge the water table, as well as specific yield and lag time.

2. MATERIALS AND METHODS

a) Site description

The study area (Tavabe-e-Arsanjan) is located in a semi-arid environment (mean annual precipitation of 325 mm with a standard deviation of 105.4 mm), about 100 km northeast of Shiraz (Fig.1). This area is located between a $53^0\,8'$ to $53^0\,24'$ east longitude and a $29^0\,39'$ to $29^0\,48'$ north latitude. The study area is among the oldest agricultural areas in the world [14]. The total area of the groundwater basin is about 380 km^2, 313.36 km^2 of which is flat, and the rest mountains. The flat area of the domain (the area of salt encrusted land near Tashk Lake not included) is 266.2 km^2. The highest and lowest elevations of the area are 2270 m in the north corner near the Siah Mountain and 1562 m in the south corner near the bank of the Tashk Lake, respectively. There is an evaporation lake (Tashk Lake) in the southeast of the study area which is extremely saline (EC = 61420 μmhos/cm). The main source of water in the study area is groundwater, as there are no rivers. Monthly water table elevation measurements dating from December 1992 were obtained in 13 observation wells dug by Fars Regional Water Authority throughout the study area. The location of these wells, labeled O.W.1 to O.W.13, is provided on Fig. 1. The value of groundwater table observations increases more with the length of the record than with the number of observation sites, because of the common dynamic components [7]. The average drop in the water table of this area has been about 0.4 m/yr over the past few years (Fig. 2), due to the high extraction rates of groundwater for irrigation and also decreasing of precipitation. All 15 existing Qanats in the study area have dried up due to the dropping water table [1]. Sampling wells for measuring groundwater quality are labeled S.W.1 to S.W. 26 as shown on Fig. 1.

b) Hydrology

The primary aquifers in the study area are composed of quaternary sediments, with thicknesses of only about 30 to 50 m in the northwest, gradually increasing toward the southeast, where the maximum thickness exceeds 300m in the vicinity of Tashk Lake (Fig. 3) [12]. These sediments are classified into two groups: pediment sediments in the northwest and marine sediments in the southeast. Since there are no rivers flowing in this area sediments are not alluvium, but pediment. The sediments consist of rubble stone, gravel, sand, and silt; and a low amount of clay [12]. The limestone in the mountainous area is in hydraulic contact with Quaternary basin deposits in many places. Mountains in the northwest of the study area are formed from the dense limestone of the Bangestan and Sarvak formations (Middle-Upper Cretaceous) [12]. This limitation combined, with the scarcity of fractures and a low degree of karstification, contribute to their insignificance. Groundwater from the limestone formations discharges only from springs which feed into the drainage system in the mountain region [14]. Discharge from the springs along the margins of the basins is used for irrigation on the plain. There are no continuous flow records for the karst springs in the upper reaches of the study area. Most springs are seasonal. Mountains in the north of the study area are formed from Dariyan and Fahliyan formations (Cretaceous) [12].

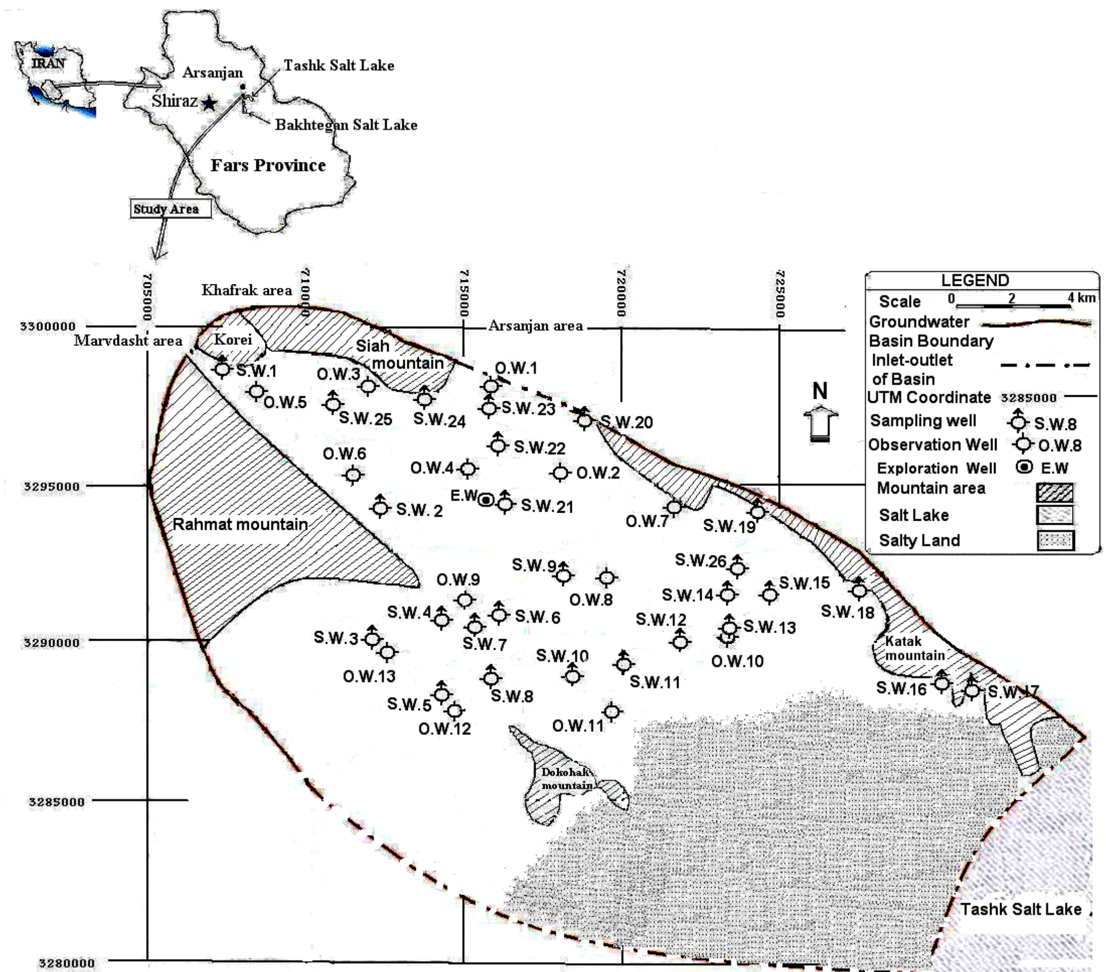

Fig. 1. Location map of the study area, observation and sampling wells

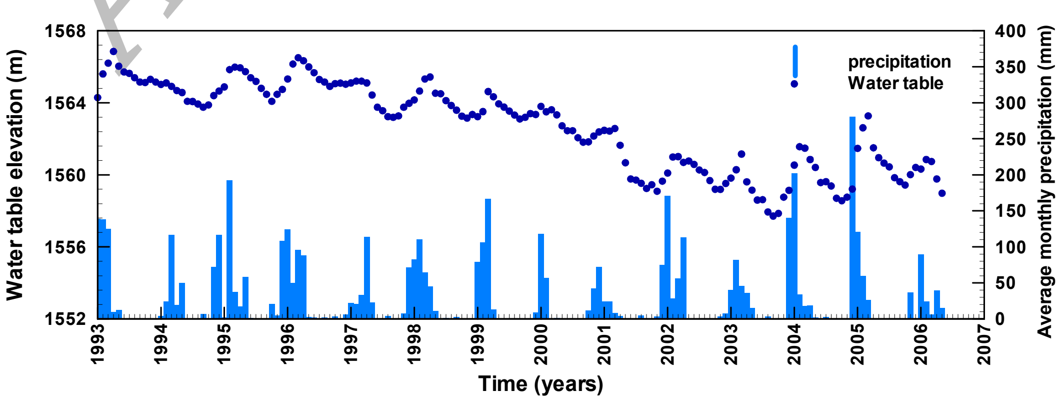

Fig. 2. Hydrograph of groundwater and hyetograph of precipitation in the study area

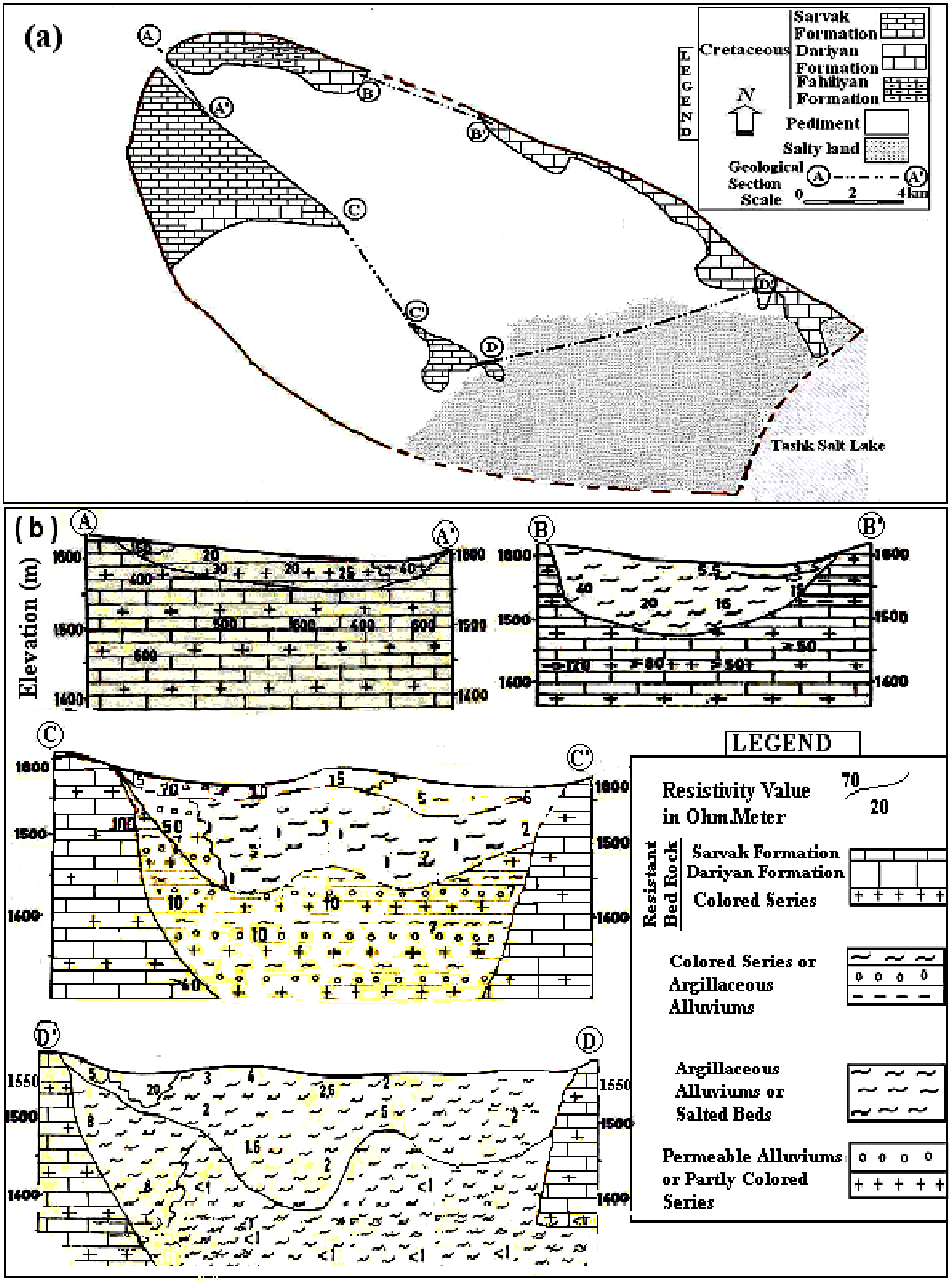

Fig. 3. a) Geologic map; b) Vertical electric sounding of the study area [12]

A single pump test was conducted to determine the hydraulic properties of the unconfined aquifer. This test was performed in the exploration well, denoted as E.W., shown on Fig. 1. This well was dug to a depth of 115 m by the Fars Regional Water Authority in 1974. Analysis of the pump test yielded a hydraulic conductivity, storativity (specific yield), and transmissivity 3.28 m/d, 3.42% and 446.6 m^2/d, respectively [1].

The pumping of groundwater in the study area before 1971 was insignificant [1]. The ground water basically retained its natural status, flowing from northwest to south and southeast. After 1987, the number of deep wells, and especially shallow wells, were rapidly increased and the pumping rate from the groundwater also increased, so the water table in this area declined (Figs. 2 and 4a). Declines in the water table caused salt water intrusion from the Tashk Lake. Fig. 4b shows the chloride (Cl^-) concentration contours at three different times. Since in coastal aquifers chloride is the predominant anion, the interest is often focused on the distribution of this ion. A classification on chloride concentrations into three main types of fresh, brackish, and saline groundwater is as follows: fresh $Cl^- \leq 300$mg/l, brackish $300 < Cl^- < 10{,}000$ mg/l and saline $Cl^- \geq 10{,}000$ mg/l [15]. Usually, the location of the contour of $Cl^- = 10{,}000$ mg/l refers to the location of the salt water/ fresh water interface. Therefore, by locating the contour of $Cl^- = 10{,}000$ mg/l in 1993, 1998, and 2004, the motion of the salt water/ fresh water interface can be judged and the advancing rate can be determined. On the other hand, in a simplistic manner (according to the Ghyben-Herzberg model), the interface between a saline water reservoir and fresh groundwater in a coastal setting can be defined, in general, as the contact zone between sea water intruding into rocks of a coastal area and the overlying fresh groundwater flowing seaward in a coastal aquifer. The geometrical relationship between the two water bodies is defined by the difference in their respective densities. The main points that emerge from this definition are: (1) there is a hydraulic connection between the fresh water aquifer and saline water; (2) the contact zone between the two water bodies can be approximately defined by the Ghyben and Herzberg equation as follows [20]:

$$h_s = \frac{\rho_f}{\rho_s - \rho_f} h_f \tag{1}$$

Where h_s is the depth of the fresh/ salt water interface below sea level (L), h_f is the piezometric head of fresh water with respect to sea level (L), ρ_f is the reference density, usually the density of fresh water (M/L^3), and ρ_s is the density of saline groundwater (M/L^3). For the ocean, where ρ_s=1,025 kg/m^3 and ρ_f= 1,000 kg/m^3, Eq. 1 can be written as follows:

$$h_s = 40 h_f \tag{2}$$

For the Tashk Lake, where ρ_s=1,041 kg/m^3, the Ghyben - Herzberg equation is as follows:

$$h_s = 24.39 h_f \tag{3}$$

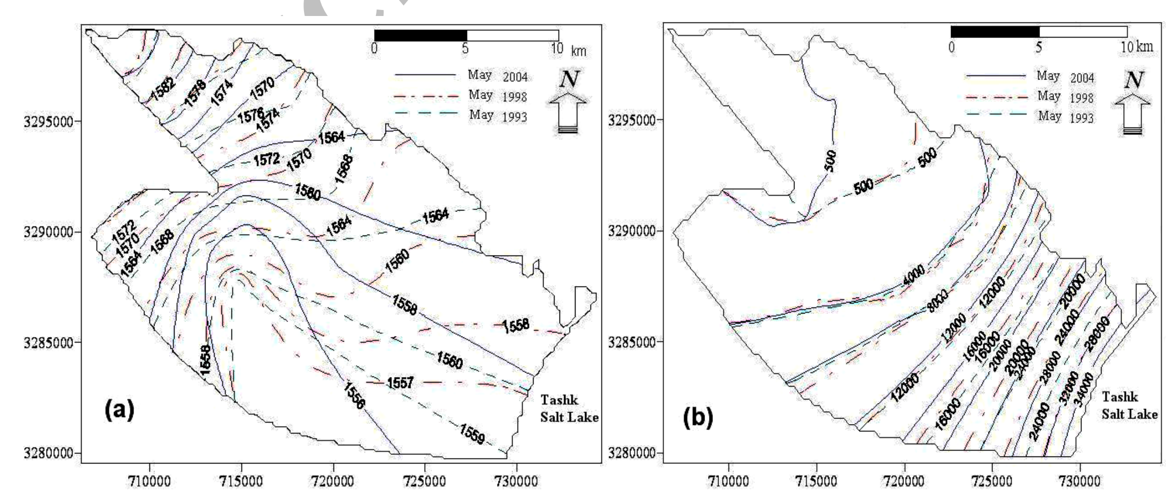

Fig. 4. a)The contour map of the observed water table elevation, and b)the contour map of the chloride concentration (Cl^-) (mg/l) for three years(May 1993, 1998, and 2004) in the Tavabe-e-Arsanjan regions

Thus, as the density of the saline component increases, the depth of the interface decreases. Due to the high density of Tashk Lake water, the interface has a much shallower slope than that near the ocean or sea (Fig. 5), so in the study area Eq. (3) should be used in the Ghyben - Herzberg model.

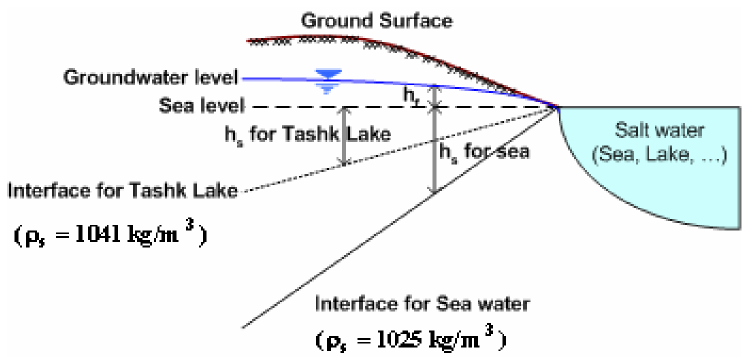

Fig. 5. Fresh / saline water interface according to the simple Ghyben-Herzberg model. Note that the interface location is shown for both regular sea water and for Tashk Lake water

Besides the two mentioned problems (salt water intrusion and shallower slope of interface), in areas where saline groundwater is present below fresh groundwater, the interface between fresh and saline groundwater may rise when fresh water piezometric heads are lowered due to well extraction. This phenomenon is called interface upconing. To study the upconing phenomenon, well number S.W.5 (Fig. 1) was selected and the pump was turned off for a period of three days. After three days, the pump was turned on and water samples were taken every hour for a period of 24 hours and the chloride concentration and electrical conductivity (EC) of the samples were measured in a laboratory by the titration (Argentometric) method and a digital conductivity-meter (Selecta CD 2002 model), respectively. Fig. 6 shows the variation of the measured Cl^- and EC with time. According to Fig. 6, Cl^- and EC increased slowly up to 1 hour after the start of pumping and then increased faster up to 3 hours before reaching an approximately constant rate. Interface upconing takes place slowly at first, and then faster, beneath the pumping well [5].

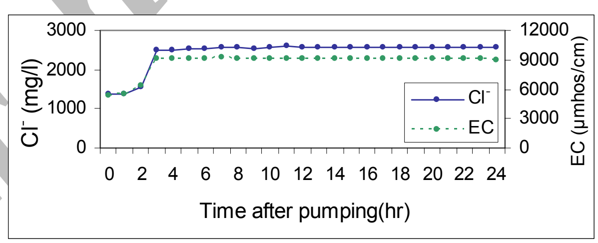

Fig. 6. Variation of EC and Cl^- concentration of pumped water with time after pumping in the study area

c) Hydrochemistry

Collected data from 26 sampling wells in the Tavabe-e-Arsanjan area (Fig. 1) indicate that there is fresh water in the northwest and saltwater in the south and southeast of the area (Fig. 4b). The chemical compositions of water samples taken from 10 representative sampling wells and Tashk Lake are shown in Table 1. The compositions of groundwater regularly varied along the flowpath from the northwest to the south and southeast in the study area. In the highland, which is in the northwest part of the study area, there is relatively natural groundwater with no contamination from Tashk Lake. According to the Piper diagram (Fig. 7) the groundwater of the study area, with the exception of northwest part, is Chloride / Sodium type.

Table 1. Chemical compositions of groundwater and Tashk Lake water in meq/L

Well No.	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	CO_3^{2-}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	NO_2^{-}	NO_3^{-}
Tashk Lake	44.00	231.00	828.951	5.07	1.6	1.40	41.00	1062.56	0.0001	0.02
S.W.1	3.50	3.70	2.26	0.07	0	1.80	2.80	3.95	0.0002	0.12
S.W.3	3.40	7.20	15.52	0.22	0	2.60	4.80	17.80	0.0002	0.04
S.W.4	2.60	6.60	12.87	0.21	0	8.00	8.80	6.30	0.0002	0.03
S.W.5	4.20	13.40	62.29	0.34	0	7.60	8.40	68.50	0.0000	0.00
S.W.6	3.80	9.30	30.40	0.32	0	9.20	10.00	26.00	0.0008	0.02
S.W.10	3.80	15.60	49.12	0.95	0	10.80	11.60	48.50	0.0001	0.09
S.W.13	6.20	22.40	100.28	0.58	0	12.10	14.00	105.62	0.0021	0.02
S.W.19	9.20	15.50	57.29	0.34	0	10.10	12.80	60.50	0.0000	0.05
S.W.21	4.00	8.40	19.74	0.19	0	5.00	5.80	22.00	0.0001	0.04
S.W.24	3.30	3.20	3.57	0.09	0	2.10	2.96	4.32	0.0002	0.03

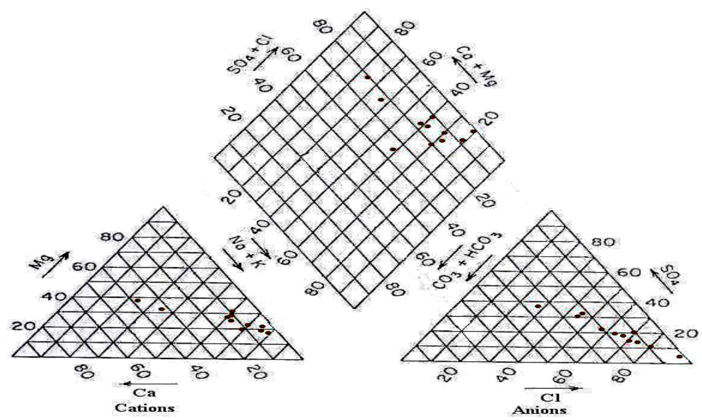

Fig. 7. Piper diagram of groundwater composition in the study area

d) Recharge study in the Tavabe-e-Arsanjan area

Several authors have presented recharge estimation methods which will not be repeated here [2, 3, 6, 9 10, 16]. The similarity between these methods is that they estimate recharge based on linkage of specific information from the atmosphere, unsaturated and saturated zones. These methods have their own limitations. Whereas one method can be applied in site specific studies, the other can be better used in regional studies.

There is insufficient information on climate, surface and subsurface hydrology factors in the study area. The only available and reliable data are precipitation and water table elevation. Therefore, the selection of a recharge estimation method was severely restricted by the availability of reliable data. So the CRD method, which is based on precipitation and water table elevation data, seems to be suitable for the study area.

1. Groundwater balance: Assuming an aquifer of area A (L^2) receiving recharge from rainfall Q_R (L^3) with production boreholes Q_p (L^3) tapping the aquifer, and with natural outflow Q_{out} (L^3) and inflow from vicinity field Q_{in} (L^3) (Fig. 8), a simple water balance equation for a given time interval i can be written as follows:

$$Q_{R_i} + Q_{in_i} = Q_{p_i} + Q_{out_i} + \Delta h_i \, A \, S \tag{4}$$

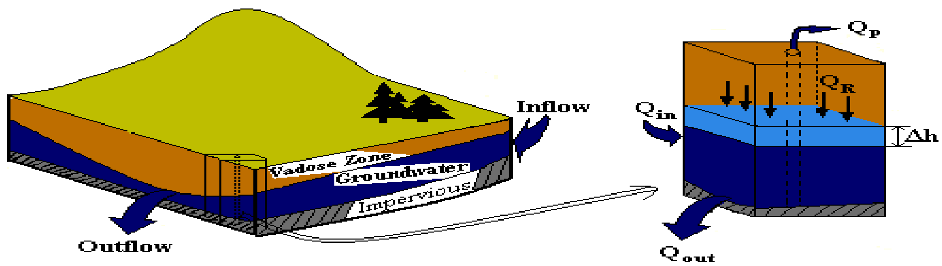

Fig. 8. Schematic of ground water balance used in CRD method

Where Δh and S are water table change (L) and storativity (specific yield), respectively. If Q_{p_i} is constant, aquifer storage (Δh_i .A. S) adjusts to accommodate for a net balance between Q_{R_i} , Q_{in_i} and Q_{out_i} . This adjustment of the storage would be reflected in the piezometric surface or water table change in boreholes. The cause-effect relationship between rainfall oscillation and water table fluctuation is effectively represented by the correlation between the CRD and water table fluctuation.

2. Theory of CRD method: CRD is defined as follows [22]:

$$CRD_i = \sum_{n=1}^{i} R_n - k \sum_{n=1}^{i} R_{av} \qquad (i = 0,1,2,3,...N) \tag{5}$$

where R is rainfall amount (L) with subscript "i" indicating the i-th month, "av" the average and k is as follows:

$$k = 1 + (Q_p + Q_{out})/(A \, \mathrm{R}_{\mathrm{av}}) \tag{6}$$

Q_p , Q_{out} and A have been defined.

It is assumed that a CRD has a linear relationship with a monthly water table change. So CRD was derived as follows:

$$\Delta h_i = \frac{r}{S} CRD_i \tag{7}$$

where Δh is the water table fluctuation (L) and r is a fraction of the CRD which results in recharge from rainfall.

Equation (7) may be used to estimate the ratio of recharge to aquifer storativity through simple regression between CRD and Δh, as reported by Xu and Tonder [22]. It is often the case that an appropriate value of the parameter k in Eq. (5) must be chosen to adequately mimic the water table fluctuation in boreholes. However, its physical meaning is still unclear [22].

Rainfall time series, in general, are composed of random and deterministic components; the latter is in the form of trends and periodicities. A short series of data often displays a trend to a certain degree, which can not be reflected in Eq. (5). A new CRD has therefore been formulated to account for such a trend by Xu and Tonder [22] as follows:

$$CRD_i = \sum_{n=1}^{i} R_n - \left(2 - \frac{\sum_{n=1}^{i} R_n}{R_{av} i} \right) \sum_{n=1}^{i} R_t \quad (i = 1,2,3,...N) \tag{8}$$

where R_t, a threshold value representing aquifer boundary conditions, is determined during the simulation process. It may range from 0 to R_{av} with 0 indicating an aquifer being closed and R_{av} implying that the aquifer system is open, perhaps being regulated by spring flow.

If the depth to the groundwater table exceeds 50m Xu and Tonder recommended that the CRD method be considered to be applied with time lags [22]. This is due to different filtering (delay) effects of rainfall passing through the unsaturated zone. For this purpose Eq. (8) is written by the authors as follows:

$$CRD_i = \sum_{n=i-l}^{i} R_n - \left(2 - \frac{\sum_{n=i-l}^{i} R_n}{R_{av}.l} \right) .l.R_t \tag{9}$$

where l is lag time. It is assumed that CRD is the driving force behind a monthly water table change if the other stresses are relatively constant. The groundwater table will rise if the cumulative departure is positive and will decline if it is negative. So the relationship between CRD and Δh was written as follows [22]:

$$\Delta h_i = \frac{r}{S}\,\mathrm{CRD_i} - \frac{Q_{p_i} + Q_{out_i}}{A.\mathrm{S}} \tag{10}$$

The term $(Q_{p_i} + Q_{out_i})/(A\ .\ S)$ in this equation is necessary only if the influence of pumping and/or outflow on water table changes is evident [22]. This model will be referred to as the revised CRD (R-CRD) model.

It seems that in the R-CRD model, for estimating water table fluctuation inflow from others, field Q_{in} was not considered. Some fields like the Tavabe-e-Arsanjan area (Fig. 3) may be connected to other fields and the inflow (Q_{in}) of groundwater occurs. Therefore, with regards to water balance (Eq. (4)), we add inflow from other aquifers to the R-CRD method as follows:

$$\Delta h_i = \frac{r}{S}\,\mathrm{CRD_i} - \frac{Q_{p_i} + Q_{out_i} - Q_{in_i}}{A.\mathrm{S}} \tag{11}$$

This equation (Eq. (11)) may be used to simulate the ratio of recharge to aquifer storativity through minimizing the difference between the simulated and observed water table series. This optimization is implemented in a user- friendly program named GREM (Groundwater Recharge Estimation Model) which is written in Visual Basic language. This optimization is based on the iteration method which is one of the Non-Derivative Methods. In Non-Derivative Methods, the model is evaluated for different parameter combinations. They are also referred to as Function Comparison Methods [11]. Logical ranges of parameters were used as constraints of the optimization model. The objective function, which is used in the Visual Basic program to minimize the difference between simulated and measured water table series, is as follows:

$$EF = 1 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i-1}^{n} \left(O_i - \overline{O}\right)^2} \tag{12}$$

where EF is the modeling efficiency [4]; O_i and S_i represent the observed and simulated values of the water table, respectively, n represents the number of observed and simulated values used in the comparison, and $\bar{O}$ is average of the observed values ($\overline{O} = \sum_{i=1}^{n} (O_i)/n$).

EF can take negative values. The negative *EF* is characterized by high variability between simulated and observed values. The zero value of *EF* shows poor simulation. If the model simulated values exactly match the observed values, then *EF*=1, [4].

In the R-CRD method, Q_p, Q_{in}, and Q_{out} parameters must be specified. According to Fig. 3, there are four sections through which the study area connects to other areas. Two of these sections are in the south and southeast and the rest are in the north and northwest. Q_{in} and Q_{out} parameters are calculated monthly using Darcy law, and Q_p is obtained from the field data.

Recorded values of the rainfall, water table, Q_p, Q_{in}, and Q_{out} from January 1, 1993 to December 31, 2000, were used for the automatic calibration procedure by GREM. Automatic calibration was performed to estimate r, R_t, and lag time. The calibration target (objective function) was based on maximizing the modeling efficiency (*EF*).

3. RESULTS AND DISCUSSION

The results show that the best values of the mentioned parameters are: r =15.2%, R_t= 4.9mm, lag time= 1 month with *EF*= 0.926. Estimated r, based on S =0.0342 obtained from the pumping test experiment in a single well, is approximately one half of 35% which was reported by Jooyab Consulting Engineers (1976) [12]. A comparison of the measured value of S with values reported in the literature for various geological materials [5, 17, 20], shows that the measured S is low and this may be the reason for obtaining a low value for r. Therefore, automatic calibration was performed using GREM to estimate S in addition to r, R_t, and lag time. The automatic calibration yields r = 33.6 %, R_t= 4.5mm, lag time= 1 month, and S = 0.097 (9.7%) with *EF*= 0.933. Obviously, the estimated value of S from an averaging process inherent in the calibration period is more realistic compared to that obtained from a single well pumping test experiment. The estimated specific yield value is consistent with the range given in the literature for geological materials in the study area [5, 17, 20]. The modeling efficiency 0.933 exhibits good agreement between the simulated and observed water table (Fig. 9).

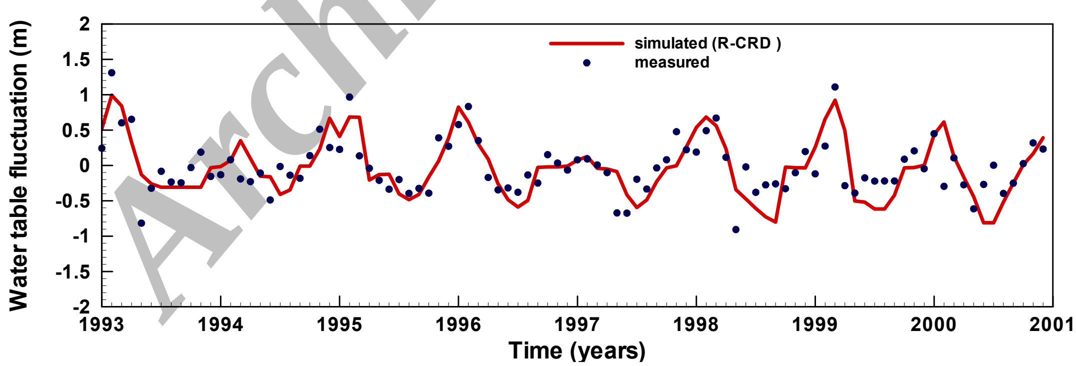

Fig. 9. Observed and simulated water table fluctuation Δh ($\Delta h = h_i - h_{i-1}$)
using R-CRD method for the calibration period

The average value of rainfall (R_{av}) is 29.62 cm (for time period of January 1, 1993 to December 31, 2000) in the study area and R_t may range from 0 to R_{av}. R_t= 4.5 mm shows that the springs do not have a significant effect on the groundwater system. Field observations show that, there are five springs just near the base of the mountains in the study area which often are dry except in a few months in winter, so they do not play a significant role in draining groundwater.

Results show a little difference between two cases: considering Q_{in} in Eq. (11) (the automatic calibration yields r = 33.6 %, R_t= 4.5mm, lag time= 1 month, and S = 0.097 with EF= 0.933) and not considering Q_{in} (the automatic calibration yields r = 34.01 %, R_t= 4.5 mm, lag time= 1 month, and S = 0.098 with EF= 0.931). The small value of Q_{in} (in our case) is the reason for this matter. According to Fig. 3, the inflow section is not large, so Q_{in} is not substantial enough to affect the results of the model. The water table fluctuation is simulated using the CRD method (Fig. 10).

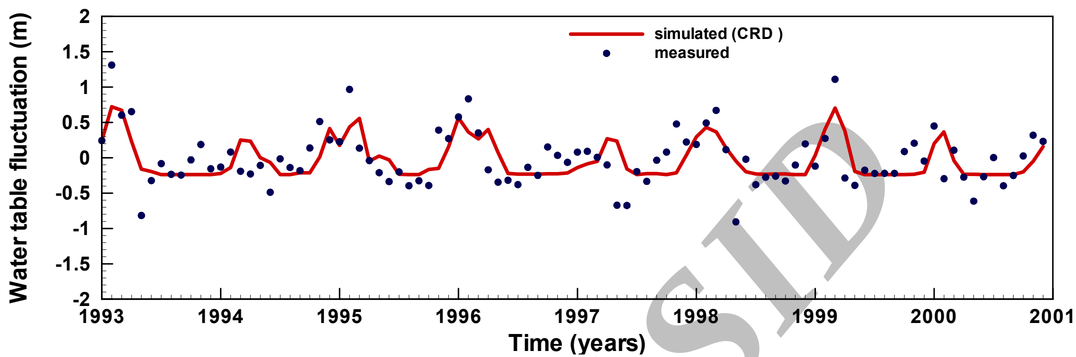

Fig. 10. Observed and simulated water table fluctuation Δh ($\Delta h = h_i - h_{i-1}$) using CRD method for the calibration period

For the validation of the models, data from January 1, 2001 to May 31, 2006 were used to test the predictive capability of the calibrated models. Water tables were simulated using the estimated parameters of the calibration period by both R-CRD and CRD models. Water table elevation, obtained from both calibration and validation periods, are shown on Fig. 11. The mean square error of simulated and observed water table elevation from January 1, 1993 to May 31, 2006 (as shown on Fig. 11) were calculated, 0.61 and 0.75 (m^2) for R-CRD and CRD, respectively. Examination of Fig. 11, as well as the calculated mean square error, show that the R-CRD method does a better job of matching the observed water table fluctuation than the CRD method.

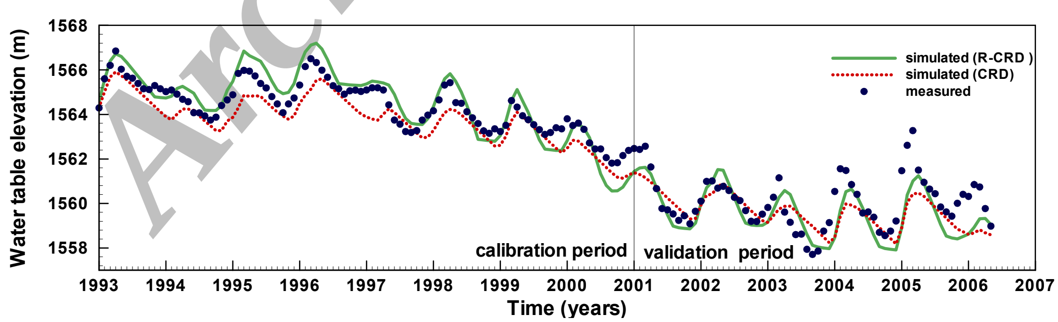

Fig. 11. Observed and simulated water table elevation using both R-CRD and CRD methods for the calibration and validation periods

One of the important parameters estimated in the optimization process by GREM is r. Estimated r implies that 33.6% of the precipitation acts to recharge the water table. With regards to Figs. 2 and 11, (decrease in water table elevation (0.4 m/year)), it can be concluded that natural recharge from precipitation is not enough for compensating the high volume of groundwater extraction in the study area.

Therefore, artificial recharge can be suggested as a countermeasure for preventing the negative balance of the water table in the study area.

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