Hydrogeologic characteristics of the alluvial tuff aquifer of northern Sahand Mountain slopes, Tabriz, Iran

A. Asghari Moghaddam · M. Allaf Najib

Abstract The Tabriz area is a densely populated area of northwestern Iran (more than 1.5 million in population) with a large proportion of its drinking, domestic, industrial and agricultural water supplied from groundwater resources. The average rate of drinking and industrial water use in the city of Tabriz is about 3.45 $m^3\ s^{-1}$. The Plio-Pleistocene unconfined alluvial tuff aquifer (about 1,275 km^2), the most important aquifer in the area, has been known for many years as a reliable resource. The greatest estimated thickness of the alluvial tuff lies in the Saidabad area, with 350 m thickness. There are 994 deep and 284 shallow active pumping wells and 83 qanats operate in the alluvial tuff aquifer. The total water withdrawal from all these artificial discharge points has been measured at 72, 3.8 and 17 million m^3/year, respectively. Analytical and numerical methods have been applied to the constant rate pumping test data from the Saidabad wellfield (eight pumping and three observation wells). The values of electrical conductivity in the groundwater of alluvial tuff aquifer range from 203 to 960 $\mu S\ cm^{-1}$ and bicarbonate type water dominates.

Résumé Le secteur de Tabriz est une région à forte densité de population au Nord-Ouest de l'Iran (population supérieure à 1.5 million d'habitants), où les ressources en eau souterraine fournissent une grande partie de l'eau potable et à usage domestique, industriel et agricole. Les besoins moyens en eau potable et industrielle de la ville de Tabriz s'élèvent à 3.45 m^3s^{-1} environ. L'aquifère libre des tuffs alluvionnaires plio-pléistocènes (environ 1,275 km^2), le plus important du secteur, est considéré depuis longtemps comme une ressource fiable. La puissance maximale estimée des tuffs alluvionnaires est de 350 m, dans la région de Saidabad. Au total 994 puits profonds et 284 puits peu profonds en activité, ainsi que 83 qanats, exploitent l'aquifère des tuffs alluvionnaires. Les prélèvements en eau totaux pour toutes ces émergences artificielles ont été estimés respectivement à 72, 3.8 et 17 millions m^3 par an. Des méthodes analytiques et numériques ont été appliquées aux données du pompage d'essai à débit constant du champ de captage de Saidabad (huits puits de pompage et trois piézomètres). Les valeurs de conductivité électrique de l'eau de l'aquifère des tuffs alluvionnaires sont comprises entre 203 et 960 μScm^{-1}, et les faciès bicarbonatés prédominent.

Resumen La región de Tabriz constituye un área densamente poblada del noroeste de Irán (más de 1.5 millones de personas) con un gran porcentaje de agua para uso doméstico, industrial y agrícola abastecido de recursos de agua subterránea. El ritmo promedio de uso de agua industrial y para consumo humano en la ciudad de Tabriz es aproximadamente 3.45 m^3s^{-1}. El acuífero de toba aluvial no confinado de edad Plio-Pleistoceno (que cubre un área de aproximadamente 1,275 km^2), el acuífero más importante del área, ha sido bien conocido por muchos años como un recurso confiable. El mayor espesor estimado de la toba aluvial se encuentra en el área Saidabad, con 350 m de espesor. Existen 994 pozos de bombeo activos profundos y 284 pozos someros y 83 qanats funcionando en el acuífero de toba aluvial. La explotación total de agua en estos puntos artificiales de descarga se ha estimado en 72, 3.8, y 17 millones m^3 por año, respectivamente. Se han aplicado métodos numéricos y analíticos a datos provenientes de pruebas de bombeo constantes del campo de pozos Saidabad (ocho pozos de bombeo y tres pozos de observación). Los valores de conductividad eléctrica en el agua subterránea de la toba aluvial varían de 203 a 960 $\mu S\ cm^{-1}$ con aguas dominantes del tipo bicarbonato.

Keywords Alluvial tuff aquifer · Analytical solutions · Numerical solutions · Tabriz (Iran) · Over-abstraction

Introduction

The extinct Sahand stratovolcanic massif, with maximum elevation of 3,700 m above mean sea level (m a.m.s.l.),

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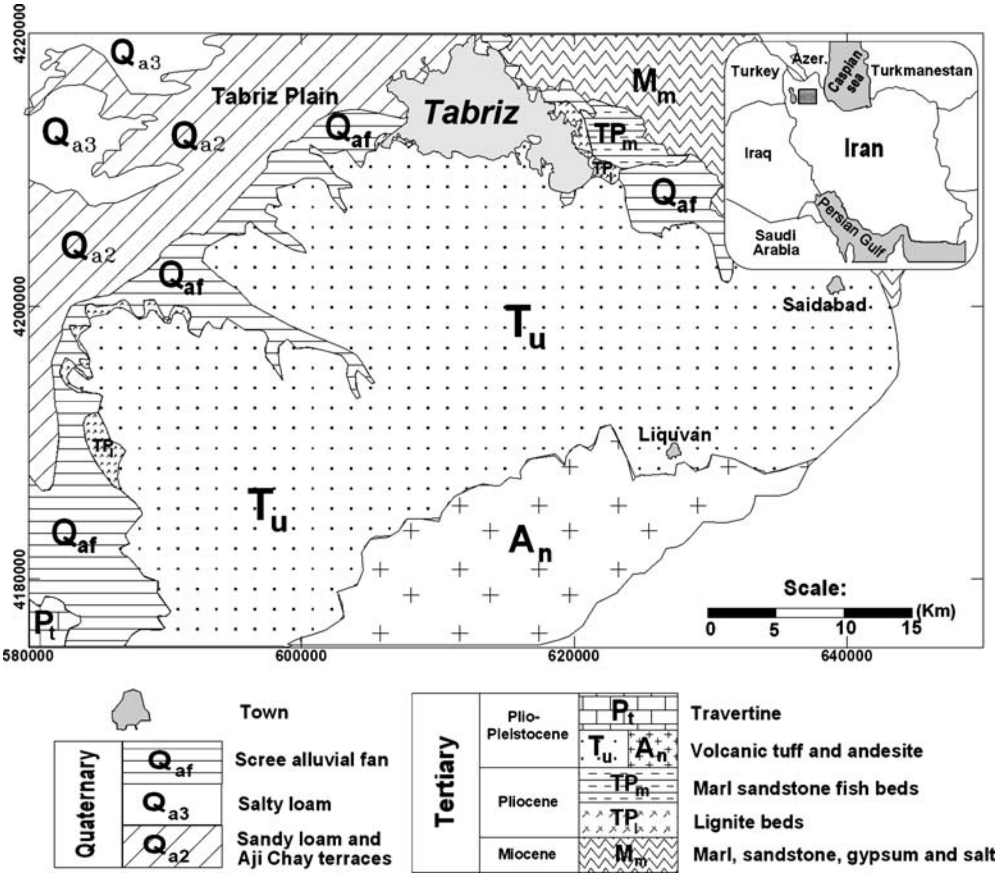

Fig. 1 Location and geological map of the northern part of Sahand Mountain slopes

occupies the southern part of the Tabriz area, in northwestern Iran (Fig. 1). It is a huge cone, deeply eroded by streams, made up of andesitic lava flows at high elevations (above 2,400 m a.m.s.l.) surrounded by pyroclastic materials reworked by water at lower elevations (roughly from 1,500 to 2,400 m a.m.s.l.), known as 'alluvial tuff'. The alluvial tuffs have relatively high elevation with very variable slope, which in general decreases towards the Tabriz Plain. At elevations between 1,500 and 2,000 m a.m.s.l., the general slope ranges from 4 to 6%. Agriculture is the main activity of the people living in the small towns and villages. Most of these activities are concentrated in the plain where the best lands are found. Generally, in the mountainous area, only narrow river valleys near the villages are able to be cultivated.

The Tabriz area is a densely populated area of Iran with a large proportion of its drinking, domestic, industrial and agricultural water supplied from groundwater resources. As a result, large volumes of water are locally withdrawn from underground storage. The rapid increase in the population, caused by migration of people from villages and small towns to the city of Tabriz, which has occurred over the past 2 years, has led to large-scale groundwater developments around this city. As a result, the water level has declined as much as 20 m during the past 20 years. According to the Statistical Center of Iran (Islamic Republic of Iran, Planning and Budget Organization 2002) publications, the population of the city of Tabriz (with an average 40-year growth rate of 3.3%) is approximately 1.4 million. The average use of drinking and industrial water in Tabriz is about 3.45 m^3s^{-1}; of this, 2.7 m^3s^{-1} is supplied by surface water and the remaining 0.75 m^3s^{-1} is from groundwater storage in the area. Migration to big cities, especially to the city of Tabriz, is the result of a shortage of water and suitable lands for agriculture elsewhere and the availability of jobs in the cities.

Andesitic tuff formations rarely form good aquifers; therefore, the alluvial tuff aquifer of the Sahand Mountain is universally unique. The purpose of this study is to consider the present groundwater resource potential, its hydrochemical conditions and its relation with surface water, as well as to describe the acceptable principles of assessment, protection and management of this vital resource.

Climate

The prevailing climate of the Tabriz area has semi-arid characteristics. During the wet season, the area is under the influence of middle-latitude westerlies, and most of the rain that occurs over the region during this period is caused by depressions moving over the area after forming

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over the Mediterranean Sea on a branch of the polar jet stream in the upper troposphere (Zolfegari 2000). In spring, air heated at ground level creates convectional precipitation, especially over the mountains. In general, the main precipitation of the area occurs during the three seasons of autumn, winter and spring, and from the third month of the autumn to end of the winter it falls as snow rather than as rain. Usually, in mountainous areas this period may by longer than 4 months. The mean annual precipitation values for the Sahand Mountain area are from 250 mm (in lowest part of the mountain) to nearly 500 mm (in the highest part of the mountain).

Mean daily temperatures at the Liquvan meteorological station (2,100 m a.m.s.l.; see Fig. 1) vary from –5 °C in January up to 17 °C in July with a yearly average of 7 °C. The dominant winds over the area blow from the northeast and the southwest. In general, mean monthly relative humidity at the Tabriz Airport meteorological station is relatively high during the November–February period, ranging from 75 to 80%, and lower during July and August, when it is about 35–45%. Pan evaporation measured at Liquvan during the water year 2001–2002 was 1,283 mm, (the water year has been fixed from 20 September to 19 September of the following year and is used in all hydrologic discussions).

River discharge

The northern part of the Sahand Mountain has five main rivers. From west to east they include the Azarshahr, Onsorrud, Sardrud, Mehranrud and Saidabad rivers. The latter two rivers usually join the Aji Chay River mostly during the wet seasons, but the others become dry in their lower parts due to percolation and evaporation losses, as well as diversion of the water for irrigation. Gauging stations are operated by Azarbaijan Regional Water Authority (ARWA) on the following main streams and tributaries: the Ghermezi-Gol station on the Gombar River (a tributary of Azarshahr River), Azarshahr station on the Azarshahr River, Zinjanab station on the Sardrud River, Liquvan and Hervi stations both on the Mehranrud River, and Saidabad station on the Saidabad River. The annual volume of water discharging at these stations is 33.8, 31.6, 9.3, 24.4, 20.0 and 10.1 million m^3, respectively.

Geological setting

The Tabriz area lies in East Azarbaijan province, which is structurally part of the Central Iran unit. It is wedged between the Zagros and Alborz mountain systems. The area includes formations of Devonian to Quaternary age affected by various geologic movements, most strongly by those of Alpine origin.

In the Pliocene epoch, there was a marine regression and a change to continental conditions, mainly lacustrine, coupled with the deposition of clay and clastics. Then, the Plio-Pleistocene marked significant volcanic activity, with lava flows and pyroclastic masses associated with the continental conditions of that epoch.

Hence, the southern part of the Tabriz area is occupied by the extinct Sahand volcano, which is built up from volcanic rocks. This massif is surrounded by volcanic sediments, alluvial tuff, which was deposited around the andesitic core. The Sahand alluvial tuff conformably overlies Pliocene marls, sandstones and fish bed (Pontian age light-colored marls containing fish skeletons) layers.

The Plio-Pleistocene volcanic tuffs have an extended exposure over 1,000 km^2 in the study area and conformably overlie the Pliocene beds to the south of the Tabriz Plain around the core of the Sahand volcano. They were formed from pyroclastic material blown out of the Sahand vents during Pleistocene times and subsequently reworked by water, hence the description of alluvial tuff.

The alluvial tuff formation is composed mainly of red and green andesitic tuff admixed with large quantities of blocks, boulders, gravel and sand of volcanic and alluvial origin. Its thickness varies from a few tens of meters at the northern end of the study area to possibly over 500 m in the south. The alluvial tuff formation thickness increases southward where it passes laterally into andesitic lavas, which flank the Sahand volcanic area. In some places, these formations are separated by a local low-permeability conglomerate or agglomerate horizon (Bayati Khatibi 2004). According to Asghari Moghaddam (1991), the Pliocene beds, which underlie Sahand Mountain tuffs, dip southwards. The bedrock of the Tabriz Basin (Pliocene and locally Miocene) is gently disturbed in the eastern part of the plain by Miocene updoming.

Hydrogeology

Through the use of qanats and an uneven distribution of drilled wells, the alluvial tuff aquifer, the most important aquifer in the area, has been known for many years as a reliable resource. It has been extensively developed as a public and agricultural water supply and has been investigated hydrogeologically, particularly in connection with groundwater development. In general, the alluvial tuff aquifer is unconfined, with water-level depth changes according to topographical and subsurface geological conditions. For example, the water level is over 100 m below ground level in the southernmost parts of the area and gradually gets closer to the ground surface towards the Tabriz Plain. In support of data from some drilled wells, geoelectrical surveys have established the thickness and limitations of the alluvial tuff aquifer (Geophysical Institute of Israel, 1964, personal communication). The resultant isopach map of this investigation is shown in Fig. 2. According to the geophysical investigations and drilled wells in the Saidabad area, the greatest estimated thickness of the alluvial tuff here is 350 m (Fig. 3) and the alluvial tuff thickness increases from the north to the south where it passes laterally into andesitic lavas.

In some areas, the boundary between alluvial tuff and alluvial fans is a geomorphological boundary between the

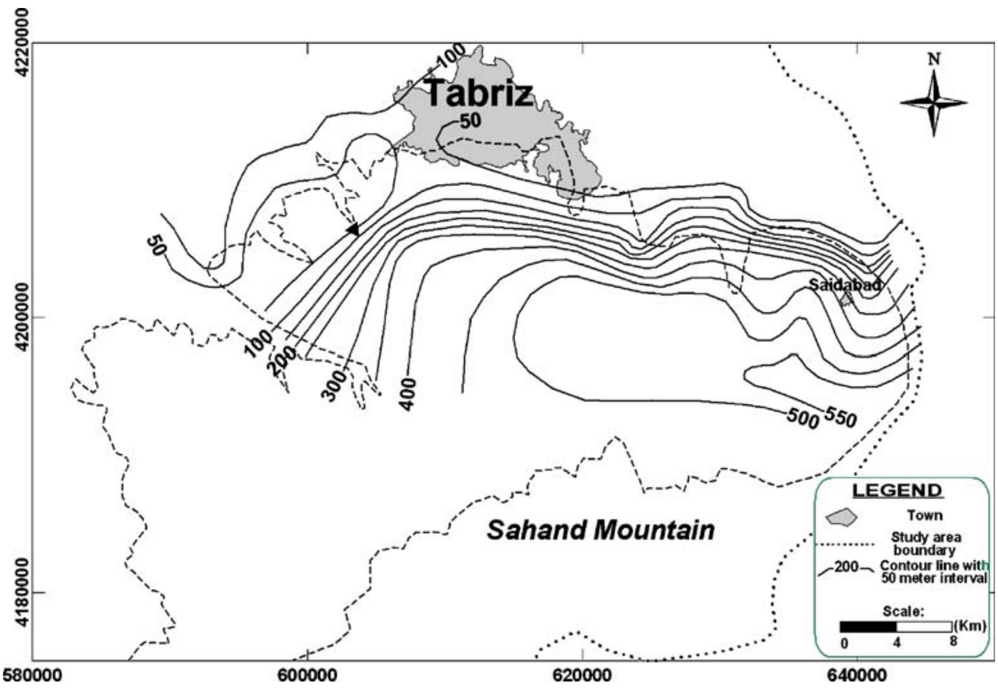

Fig. 2 Isopach map showing thickness of the alluvial tuff aquifer

plain and mountain. While in other areas, they are separated by Pliocene marls and fish beds, which lie below the tuff (Fig. 1). The fans and alluvial tuff are bordered to the northeast by upper and middle Miocene and Pliocene marl, sandstone, schist, gypsum and fish beds; to the south by the andesitic lavas of the Sahand Mountain; to the west and northwest by the Jurassic marly calcareous schist and Plio-Pleistocene travertine and quaternary sand and salty loams respectively.

In the Tabriz Plain itself, there are two types of aquifers: (1) an unconfined aquifer which includes the southern, northern and central alluvial fans and pervious terrace materials, and (2) the multi layer aquifer system which mainly lies in the central plain as well as in the Aji

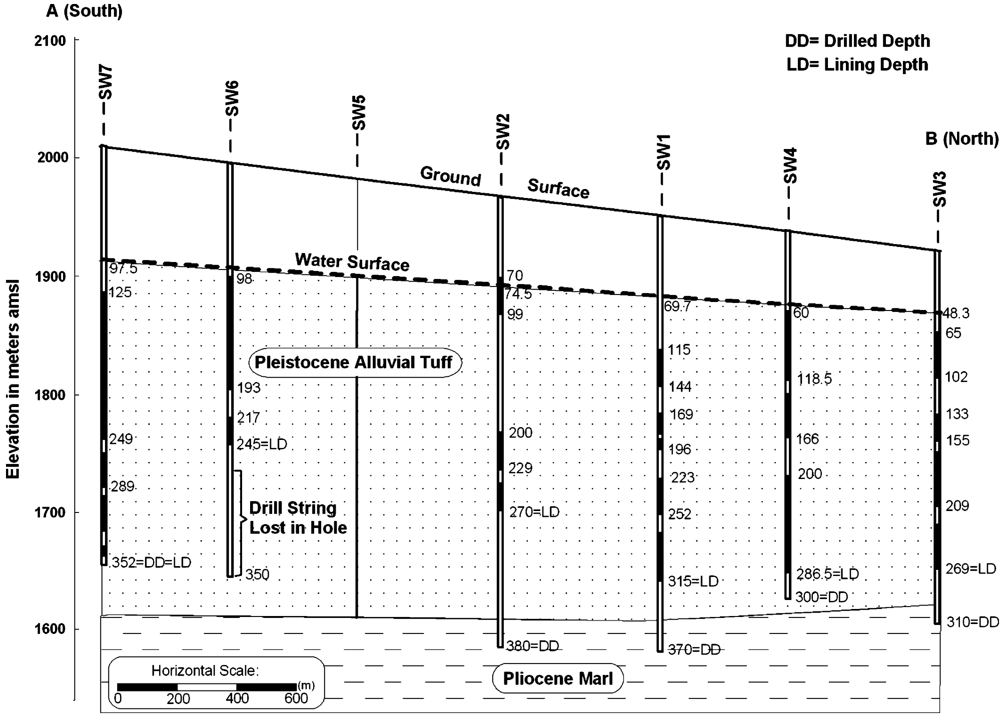

Fig. 3 Geological section through Saidabad exploratory wells (SW1–SW7, located in Fig. 7)

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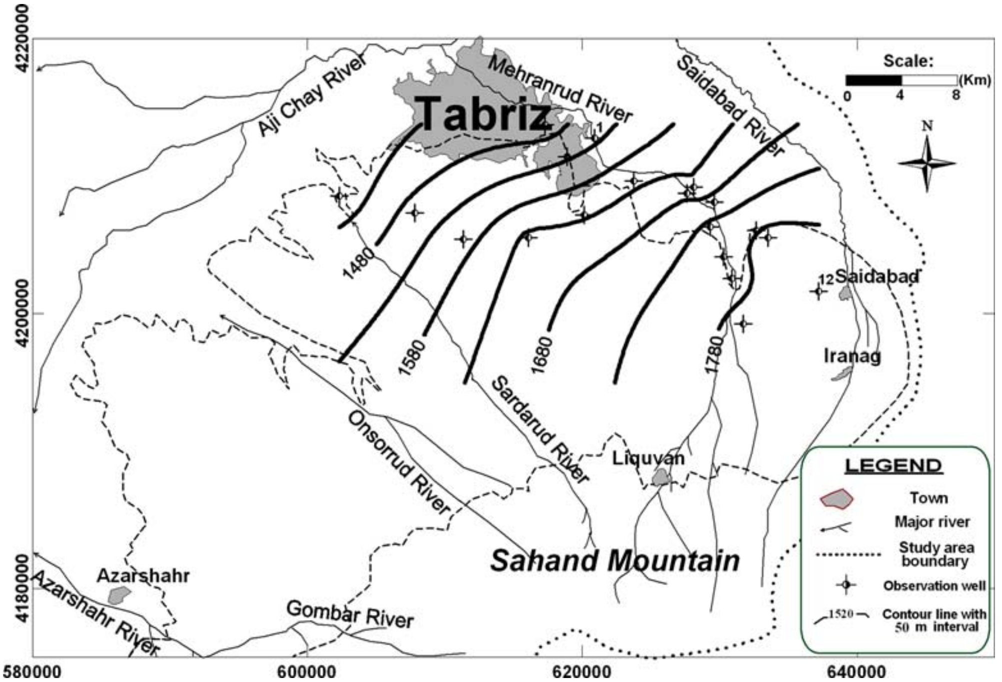

Fig. 4 Groundwater level contours (m a.m.s.l.) for May 2002 and location of monitoring wells

Chay River terraces and buried channel formations. Groundwater in the alluvial tuff aquifer supplies the water resources of the southern and central parts of Tabriz Plain aquifers.

According to Azarbaijan Regional Water Authority (Azarbaijan Regional Water Authority 2003), 994 deep and 284 shallow active pumping wells and 83 qanats operate in the alluvial tuff aquifer. The total water withdrawal from all these artificial discharge points was measured during August 2002 and generalized for the whole year by the ARWA as 72, 3.8 and 17 million m^3/year respectively. Therefore, the total artificial groundwater withdrawal from the alluvial tuff aquifer is about 92.8 million m^3/year.

Groundwater level fluctuations

Groundwater level fluctuations can result from a wide variety of hydrological phenomena, some natural such as groundwater recharge, evaporation, and meterological phenomena, and some human-induced such as groundwater pumping, deep well injection, artificial recharge and agricultural irrigation and drainage. In many cases, there may be more than one mechanism operating simultaneously, therefore, it is important that the various phenomena be understood. The time variations in groundwater levels can be considered as (1) long-term, (2) seasonal, and (3) short-term in duration. In overdeveloped basins, where extraction exceeds recharge, a drawdown trend in groundwater levels may continue for many years. The seasonal fluctuations usually result from influences of rainfall, bank storage, and pumping for irrigation, all of which follow well-defined seasonal cycles.

Monthly fluctuations of groundwater level have been measured in the alluvial tuff aquifer since 1982. Figure 4 shows the locations of the 19 groundwater level monitoring wells and groundwater level contours for May (2002) in this aquifer. Data obtained from two of these wells (well nos. 1 and 12 in Fig. 4) are plotted on an arithmetic scale as long-term well hydrographs (Fig. 5). The long-term and severe decline of groundwater level is shown in monitoring well number 12 in Fig. 5 (50 m per 20 years). Monitoring well number 12 is located near the Saidabad well field, which supplies the major portion of the city of Tabriz's drinking water. The wells are in operation throughout the year; therefore, the water level in this area is continuously and sharply declining. However, the seasonal fluctuations are not readily apparent in the monitoring well in this area due to the nearby location of some of the drinking and industrial water-supply wells, as well as the fact that they are masked by the long-term decline of the water level. Monitoring well number 1 shows less long-term decline and well-defined seasonal fluctuations (Fig. 5). Well number 1 is inside the city of Tabriz and there are no abstraction wells in this area; therefore, there is no significant long-term decline in groundwater levels in Tabriz. About 51, 21.5 and 2.9 million m^3 of water abstracted annually from the alluvial tuff aquifer supplies, respectively, the drinking, agricultural and industrial water demands for the city of Tabriz and other small towns. Long-term and seasonal average areal water-level fluctuations recorded in the 19 monitoring wells are plotted in Fig. 6. The mean values are calculated by creating Thiessen polygons for some of the monitoring wells. The seasonal fluctuations and long-term decline of groundwater levels in the area are evident in this average areal well hydrograph.

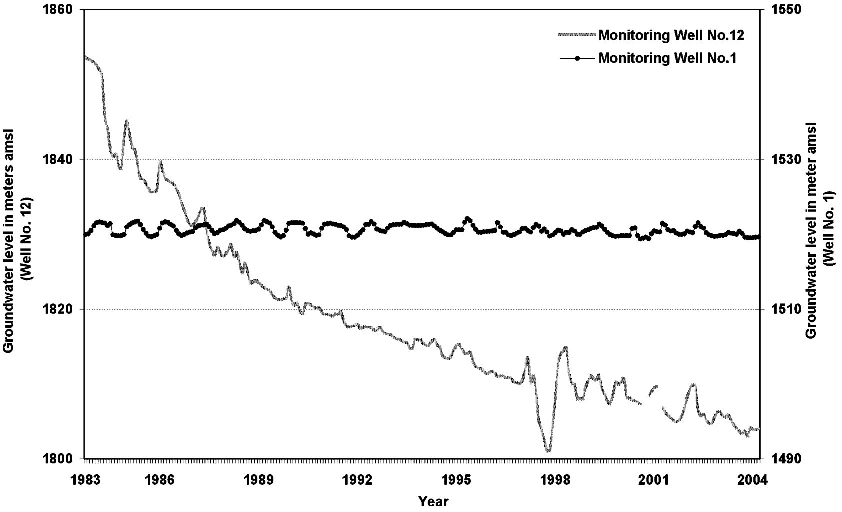

Fig. 5 Long-term and seasonal groundwater level fluctuations

Aquifer hydraulic properties

One of the most important aspects of groundwater resources investigation is the determination of aquifer properties by analyzing data obtained from well pumping tests. Data representative of this aquifer come from the Saidabad well field using eight pumping and three observation wells. Actually, there are data recorded for thirteen pumping wells, but five were not analyzed because of their close distance to other wells in the well field. The total area of the well field is about 100 km^2 and is located 2 km from the village of Saidabad (see Fig. 7).

Time-drawdown and recovery data from wells SW1, SW3, SW7, and their respective observation wells SPW1, SPW3, and SPW7 (within 50 m of the pumping wells, but not shown in Fig. 7) as well as single pumping wells SW5, SW8, SW10, SW11, and SW13 were analyzed by numerical and different analytical methods.

All the above-mentioned wells were drilled in 1977 by IRAB Engineering Company Limited, using conventional rotary techniques. In some wells, particularly in the northern part of the well-field area, the drilled holes fully penetrate the homogeneous alluvial tuff aquifer. A summary of the total and completed depth of wells is presented in Table 1.

The time drawdown and recovery data for pumping and observation wells of this well field were plotted and analyzed using Cooper and Jacob (1964) straight line and Theis (1935) type-curve methods. The results of the analyses are summarized in Table 2 (Asghari Moghaddam 1991). The time drawdown and recovery analyses are in close agreement with one another except for well SW8. The resultant values of transmissivity obtained from this method range from 230to 1,150 m^{2}day^{-1}.

Rushton, with contributions from others (Rushton and Booth 1976; Rushton and Chan 1976; Rushton and Redshaw 1979; Rushton and Rathod 1988; Rushton and Srivastava 1988 and Rushton 2003), has developed a numerical technique for analyzing pumping tests data. This method has advantages in that many factors can be included in a single numerical solution. These factors are listed by Jones and Rushton (1981) as: (1) well of finite

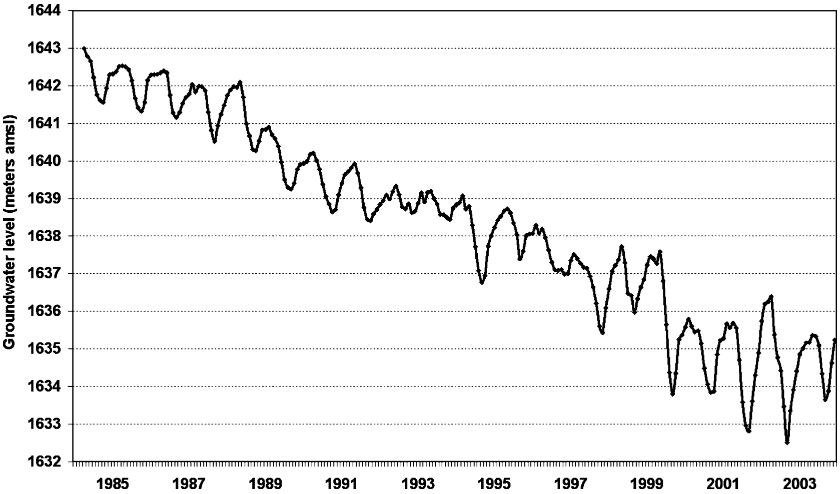

Fig. 6 Long-term and seasonal average areal groundwater level fluctuations in the alluvial tuff aquifer; data is from 19 monitoring wells

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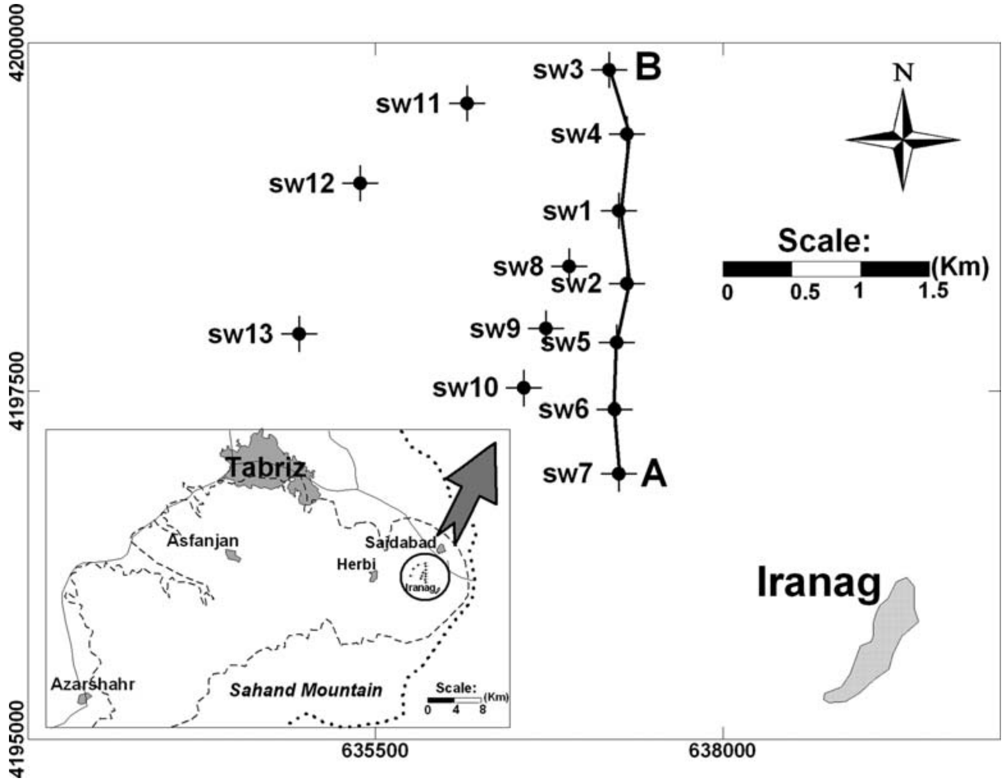

Fig. 7 Saidabad well field and location of pumping wells

radius, (2) free water contained within well, (3) variations in abstraction rate including zero abstraction rate (recovery), (4) outer boundaries either impermeable or zero drawdown, (5) variable saturated depth, (6) permeability which varies with radius or depth, (7) storage coefficient which varies with depth or radius including change between confined and unconfined conditions, (8) leaky aquifers, (9) intermittent recharge, (10) delayed yield from storage and (11) non-linear well losses. However, the accuracy of the results depends on the reliability of the field data and the supplementary information obtained from the analytical methods. In trying to match the radial flow model curve to the field data, it is possible that by varying different model parameters, an equally good agreement could be obtained. Additional and reliable information about the aquifer is needed before it can be stated with certainly that the parameters deduced in the foregoing analysis are the correct parameters. Full details of the numerical technique are given by Rushton and Redshaw (1979), and only the basic approach is summarized below.

Table 1 Screen length, and lined and drilled depths of pumping and observation wells (meters below ground level)

Well No.	Screen length (m)	Lined depth (m)	Drilled depth (m)
SW1	131.8	315	370
SPW1	132.0	315	315
SW3	139.1	269	310
SPW3	140.0	269	269
SW5	178.0	340	360
SW7	190.3	352	352
SPW7	190.0	352	352
SW8	168.4	337	345
SW10	175.7	330	350
SW11	219.5	320	333
SW13	88.4	203	242

SW pumping well, *SPW* observation well

The non-steady state equation describing radial flow in an aquifer is:

$$\frac{\partial}{\partial r}\left(bK_r\frac{\partial s}{\partial r}\right)+\frac{b}{r}K_r\frac{\partial s}{\partial r}=S\frac{\partial s}{\partial t}+q \qquad (1)$$

Where s = drawdown below datum, r = radial co-ordinate, b = saturated thickness of aquifer, K_r = radial permeability, t = time, S = storage coefficient (confined and unconfined), and q = recharge per unit area.

This equation is solved by creating a new variable:

$$a=\log_e r \qquad (2)$$

Then, substituting this variable in Eq. 1 and multiplying through by r^2, leads to the equation:

$$bK_r\frac{\partial^2 s}{\partial a^2}=Sr^2\frac{\partial s}{\partial t}+qr^2 \qquad (3)$$

The solution to this equation with appropriate boundary and initial conditions, assuming a regular mesh

Table 2 Analytical method pumping test analysis results from the Saidabad well field by straight line method

Well No.	Time-drawdown		Time-recovery	
	T (m^{2}d^{-1})	S_{con}	T (m^{2}d^{-1})	S_{con}
SW1	453	–	365	–
SPW1	911	5.510^{-3}	1151	8.63×10^{-3}
SW3	584	–	584	–
SPW3	684	2.18×10^{-3}	820	2.36×10^{-3}
SW5	654	–	576	–
SW7	351	–	395	–
SPW7	374	1.95×10^{-3}	575	7.55×10^{-4}
SW8	498	–	282	–
SW10	489	–	514	–
SW11	518	–	553	–
SW13	233	–	231	–

S_{con}. confined storage, *SW* pumping well, *SPW* observation well, *T* Transmissivity

interval Δa and an approximated finite difference, can be written as:

$$\frac{bK_r}{\Delta a^2}\left(s_{n-1}-2s_n+s_{n+1}\right)_{t+\Delta t}=\frac{Sr^2}{\Delta t}\left(s_{n,\Delta t}-s_{n,t}\right)+q_{t+\frac{1}{2}\Delta t}r_n^2 \qquad (4)$$

The use of mesh spacing with constant increments of Δa results in a fine mesh in the vicinity of the abstraction well and more widely spaced at greater distances. A time increment t to $t+\Delta t$ is also used logarithmically.

It is possible to visualize Eq. 4 in terms of equivalent hydraulic resistances which are defined as:

$$H_n=\frac{\Delta a^2}{bK_r} \qquad (5)$$

$$T_n=\frac{\Delta t}{Sr_n^2} \qquad (6)$$

Where H_n=equivalent hydraulic resistances and T=transmissivity, by substitution into Eq. 4, the equation for node n becomes:

$$\frac{\left(s_{n-1}-2s_n+s_{n+1}\right)_{t+\Delta t}}{H_n}=\frac{s_{n,t+\Delta t}-s_{n,t}}{T_n}+qr_n^2 \qquad (7)$$

The recharge at node n is given by:

$$q=\frac{-Q}{A_n} \qquad (8)$$

where Q = well discharge rate and A_n=area represented by node 1 and =$2r\Delta_r$.

$$\text{Since}\quad a=\log_e r,\quad \Delta_r=r\Delta_a$$
$$\text{and}\quad A_n=2r^2\Delta_a\quad \text{Then}\quad q=-\frac{Q}{2r^2\Delta_a}$$

The equations represented in the program (Rushton and Redshaw 1979) are calculated by substituting node n and node 1 in the above mentioned equations associated with some assumptions; where node 1 represents the whole of the region within the well, the radius is $R(2)$ and the outer boundary is R(NMAX). The increment is Δa=0.38376 and there are six mesh intervals for a tenfold increase in radius, with the finite interval ending at R(NMAX).

When the delayed yield (ALPHA) is incorporated in the discrete model, the quality of water per unit area entering a typical node of the aquifer during the nth time interval will be determined.

When well losses occur, additional drawdown results due to turbulent flow and well clogging. This effect can be modeled by reducing the hydraulic conductivity by a multiplication factor for the node closest to the pumping well. For the pumping test analyses from the Saidabad well field, it was reduced in nodes 2 and 3 of the pumping wells.

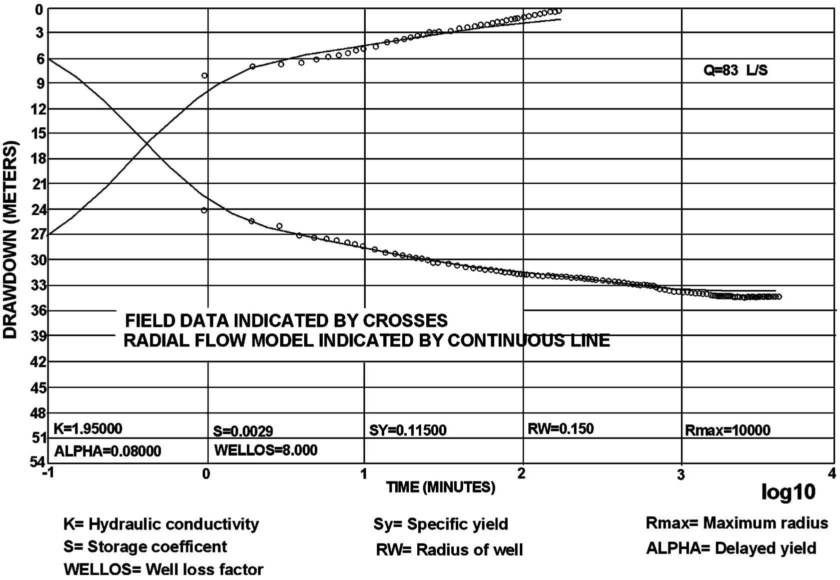

Fig. 8 Pumping well SW1 analysis with recovery

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Table 3 Numerical method pumping test analysis results from the Saidabad well field (1991)

Well No.	b (m)	K (md^{-1})	T (m^{2}d^{-1})	$S_{con.}$	S_y	WLF	α(d^{-1})
SW1	245	1.95	478	2.9×10^{-3}	1.25×10^{-1}	8.0	0.045
SPW1	245	3.50	858	5.0×10^{-3}	1.8×10^{-1}	1.0	0.08
SW3	222	2.68	595	2.9×10^{-3}	1.15×10^{-1}	6.0	0.06
SPW3	222	2.50	555	2.9×10^{-3}	1.35×10^{-1}	1.0	0.16
SW5	277	2.37	656	1.5×10^{-3}	1.25×10^{-1}	11.0	0.12
SW7	300	1.08	324	2.4×10^{-3}	2.7×10^{-1}	2.0	0.02
SPW7	300	1.20	360	2.4×10^{-3}	2.7×10^{-1}	1.0	0.04
SW8	267	1.80	481	3.0×10^{-3}	1.65×10^{-1}	6.0	0.10
SW10	253	1.85	468	3.0×10^{-3}	1.1×10^{-1}	6.0	0.04
SW11	289	1.65	477	3.0×10^{-3}	1.6×10^{-1}	6.5	0.10
SW13	230	1.05	242	6.0×10^{-3}	2.4×10^{-1}	8.4	0.10

b saturated thickness of Aquifer, *K* hydraulic conductivity, *T* transmissivity, S_{con}. confined storage, S_y specific yield, *WLF* well loss factor, α delayed yield, *SW* pumping well, *SPW* observation well

Each pumping and observation well that was analyzed by Theis and Jacob analytical methods was also analyzed by the Modified Rushton numerical-test pumping model written in Fortran 77. The position of the observation well and the results of hydraulic properties from the analytical methods were set in the model data file. The theoretical radial flow model curve determined by the numerical technique was fitted to field data plotted on semi-logarithmic paper. Best fit matching was tried by changing the values of the related parameters until the best agreement was achieved (see Fig. 8). The time drawdown and recovery data for the other pumping wells of this well field were run and compared with the radial flow model results. The resultant values of transmissivity and storage coefficient for the well field range from 240 to 900 m^2 day^{-1} and 2.7×10^{-1} to 1.1×10^{-1} respectively. The final results for the well field are summarized in Table 3.

As explained previously, many factors influence drawdown at the abstraction well in an unconfined aquifer. These factors include the transmissivity (hydraulic conductivity × saturated aquifer thickness), confined and unconfined storage coefficients, delayed yield, modified transmissivity in the vicinity of the abstraction well, the free water contained within the well, and the influence of the boundaries as well as the abstraction rates (Rushton 1978). Some of these are known and constant, whereas others depend on the type of aquifer. The following parameters are variable: permeability, storage coefficients, delayed yield, and well loss factor. The numerical model can include all these factors in a single numerical analysis but using this, in many cases, it is difficult to distinguish the relative importance of their roles.

The well loss factor for observation well SPW1 (see Table 3) is equivalent to one, which means that there is no well loss in the observation wells. By comparison, this value for the associated pumping well (SW1) is 8.0 which is equivalent to a horizontal hydraulic conductivity of one eighth of the normal value at a distance of 7 cm from the well face. There is good agreement between the transmissivity values deduced from this method and the analytical

Table 4 Hydrochemical data of alluvial tuff aquifer (June 2003)

Sample No.	UTM		CB error	EC μS cm^{-1}	pH	mg l^{-1}							
	X	Y				Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^{-}	CO_3^{-}	SO_4^{--}	Cl^{-}
1	607500	4207400	2	586	8.6	47.4	9.2	55.4	6.7	146.4	15	71.0	55.1
2	639400	4195300	2.6	245	8.4	27.7	2.7	15.4	3.7	109.8	10.5	6.2	7.5
3	628900	4207400	0.8	841	6.7	92.8	19.0	51.6	5.3	353.8	0	60.2	48.7
4	639300	4204900	0.9	507	8.2	63.5	9.2	27.3	3.6	225.7	6	20.0	28.0
5	619500	4205250	0.5	770	8.2	79.5	12.2	65.3	5.7	268.4	6	79.0	57.5
6	628250	4204500	1.1	272	8.5	24.5	3.2	25.4	3.6	97.6	12	12.1	13.0
7	622300	4205600	0.1	612	8.2	64.7	8.4	47.5	5.1	207.4	4.5	70.0	38.6
8	628850	4203850	3.1	252	7.1	22.9	1.7	23.1	3.3	115.9	0	13.0	12.5
9	611200	4205600	0.2	612	8.6	55.4	9.0	59.5	6.6	207.4	15	47.0	48.1
10	631200	4202000	1.2	267	7.4	23.7	5.6	18.5	4.1	115.9	0	12.0	12.0
11	625400	4207100	0.7	556	8.1	51.4	10.2	45.0	5.0	170.8	3	79.6	30.0
12	637400	4199400	0.7	402	7.4	47.4	3.5	31.3	5.7	207.4	0	14.0	14.5
13	636800	4204500	3.4	331	8.4	36.5	4.1	21.8	4.2	97.6	10.5	54.1	13.0
14	621900	4208100	0.8	631	8	41.8	12.0	66.8	6.0	225.7	1.5	75.0	32.5
15	624800	4205500	0.3	204	8.4	24.1	1.0	15.4	2.9	91.5	9	0.6	7.0
16	633400	4203200	0.9	203	7.7	21.7	1.0	16.1	3.3	103.7	0	4.0	7.0
17	625250	4209000	0.3	745	8.7	91.6	11.2	45.0	5.6	286.7	18	60.0	35.0
18	627400	4208400	2	517	8.5	40.6	1.0	47.5	5.5	164.7	12	61.0	30.6
19	628000	4209250	0.3	961	8.2	76.7	24.1	87.7	7.1	292.8	4.5	131.3	72.6
20	630100	4198000	0.8	339	8.5	41.8	1.7	23.6	4.3	146.4	15	6.2	13.5

UTM universal transverse mercator, *CB* charge balance

Table 5 Hydrochemical data of rivers (June 2003)

Station name	UTM		CB error	EC μS cm^{-1}	pH	mg l^{-1}						
	X	Y				Ca^{++}	Mg^{++}	Na^{+}	K^{+}	$\mathrm{HCO_3}^{-}$	$\mathrm{SO_4}^{--}$	Cl^{-}
Saidabad	639160	4205370	1.03	529	7.3	56.9	9.2	39.1	4.3	189.7	80.2	18.8
Zinjanab	616760	4189820	2.02	205	7.9	22.4	3.4	11.5	2	97.9	2.4	13
Ghermezi-Gol	587890	4178060	2.2	154	8.1	19.2	2.9	6.9	1.6	79.6	0.5	7.5
Hervi	630750	4199860	0.15	333	7.5	39.7	5.1	13.8	14.8	165.2	17.3	12.4
Liquvan	626290	4188400	0.62	408	7.3	32.5	13.9	11.5	32	177.5	26.5	22.5

UTM universal transverse mercator, *CB* charge balance

analyses. The storage coefficients and delayed yield values shown a small range of variation.

Hydrochemistry

The chemical and biological characteristics of groundwater determine its usefulness for industry, agriculture, and the home. The study of groundwater chemistry provides important clues about the geological history of the water-bearing layers, and gives some indication of groundwater recharge and the velocity and direction of flow patterns and storage.

Groundwater samples have been collected by Azarbaijan Regional Water Authority twice a year (June and October) since well completion from about 25 selected points, including 18 deep wells and 7 shallow wells distributed over the alluvial tuff aquifer. Some of the well samples that contain very similar major constituents, and are close to each other, were ignored and only 20 of them are shown in Table 4. The sample preservation and analyzing techniques were in accordance with the 17th edition of the Standard Methods (Clesceri et al. 1989). The average electrical conductivity (EC) is 493 μS cm^{-1}. The lower values of EC may result from high velocity of groundwater and lower solubility of the aquifer materials. The pH value for the aquifer is high and it ranges from 7.1 to 8.6. This may be due to alteration of feldspars and micas to clay, which is accompanied by a rise in pH and $\mathrm{HCO_3}^{-}$ concentration of water (Freeze and Cherry 1979). Ca^{2+} is dominant over Mg^{2+}, $\mathrm{HCO_3}^{-}$ is more than Cl^{-} and $\mathrm{SO_4}^{--}$ and Na^{+} is also dominant over K^{+}, as sodium is

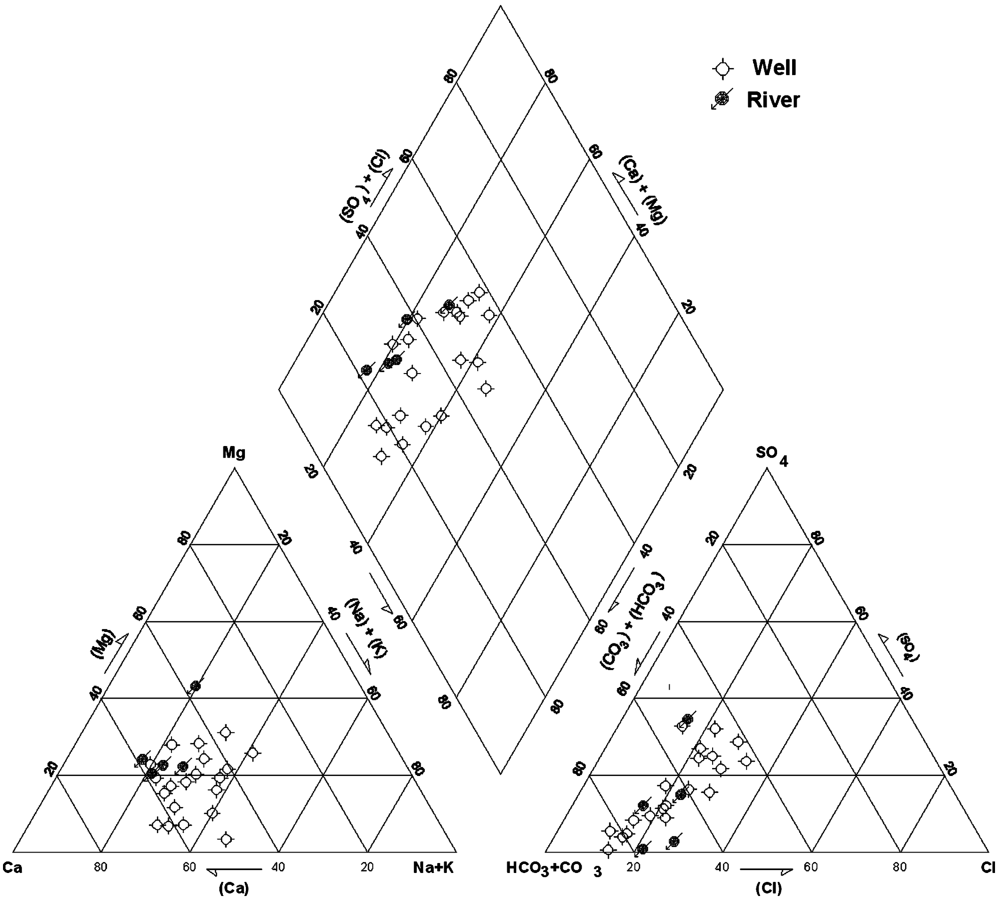

Fig. 9 Chemical constituents of alluvial tuff aquifer groundwater and rivers water by Piper diagram

more soluble than potassium (Singhal and Gupta 1999). Also, water samples collected at five of the stations on four of the rivers mentioned above were analyzed for major ions; results are shown in Table 5. The values of EC in the rivers' water range from 154 to 529 μS cm^{-1} which is lower than the EC range of the aquifer.

The analytical results of the 20 groundwater samples and 5 river samples were plotted on a Piper diagram (Fig. 9). According to Hounslow (1995), four basic conclusions can be derived from multiple analyses plotted on Piper diagrams. These are water type, precipitation or solution, mixing, and ion exchange. The water samples plotted near the left corner of the diamond, in the region of temporary hardness, are rich in Ca^{2+} and HCO_3^-. Therefore, in general, the groundwater of the alluvial tuff aquifer is of the $Ca^{2+}HCO_3^-$ type. Because of the homogeneity and pyroclastic characteristics of the aquifer formation, mixing of different types of groundwater and ion-exchange conditions is not possible. Due to the high hydraulic gradient of the groundwater and low solubility of the pyroclastic rocks, total dissolved solids (TDS) values of the water samples are low; thus, solution of aquifer materials must be occurring along the flow direction.

Conclusions

The prevailing climate of the Sahand Mountain area has semi-arid characteristics with mean annual precipitation values from 250 mm (in lowest part of the mountain) to near 500 mm (in the highest part of the mountain).

Through the use of qanats and drilled wells, the unconfined alluvial tuff aquifer, the most important aquifer in the area, has been known for many years as a reliable resource. From a geological point of view, the Plio-Plestocene alluvial tuffs are composed mainly of red and green andesitic tuff admixed with large quantities of blocks, boulders, gravel, and sand of volcanic and alluvial origin. Its thickness varies from a few tens of meters at the northern end of the aquifer to about 500 m in the south. In some places, these formations are separated by a local low-permeable conglomerate or agglomerate horizon.

Total artificial groundwater withdrawal from this aquifer is about 92.8 million m^3 per year. Maximum and minimum long-term groundwater level decline in monitoring wells is from about 2.5 m/year to a few centimeters, respectively.

The pumping test data representative of the alluvial tuff aquifer comes from the Saidabad well field using eight pumping and three observation wells. The time drawdown and recovery data from these pumping and observation wells were analyzed by analytical and numerical methods. The resultant values of transmissivity and storage coefficient for the well field range from 240 to 900 $m^2 day^{-1}$ and 2.7×10^{-1} to 1.1×10^{-1} respectively.

The average value of EC for the alluvial tuff aquifer is 493 μS cm^{-1}. The lower values of EC may be the result of the high velocity of groundwater and low solubility of the aquifer materials. The pH value for the aquifer is high and it ranges from 7.1 to 8.6. In general, the groundwater is of a $Ca^{2+}HCO_3^-$ type.

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