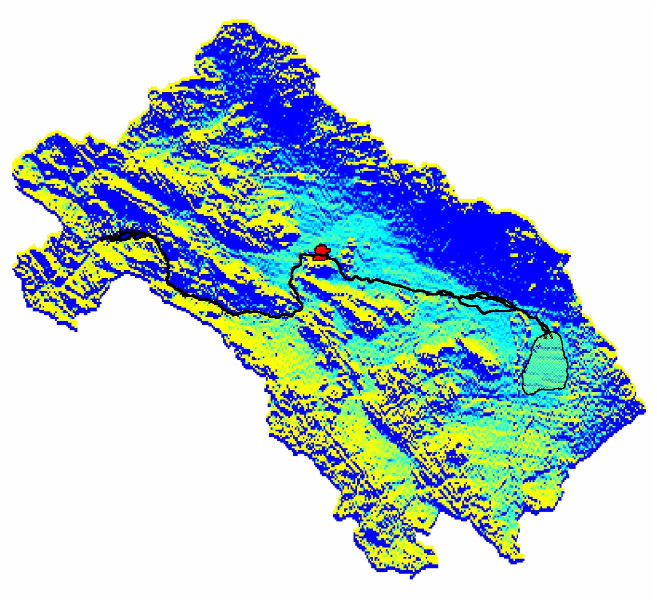
Sustainable Irrigation and Water Management in the Zayandeh Rud Basin, Iran

Groundwater Chemistry of the Lenjanat District, Esfahan Province, Iran

A. Gieske, M. Miranzadeh, A. Mamanpoush



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Groundwater Chemistry of the Lenjanat District, Esfahan Province, Iran

A. Gieske, M. Miranzadeh, A. Mamanpoush

Abstract

A hydrochemical analysis is made of the groundwater and surface water in the Lenjanat District, which lies between Esfahan and Chadegan Dam along the Zayande Rud. The analysis is based on two data sets, both kindly made available by the Ministry of Energy (Esfahan Regional Water Organization). The first one consists of chemistry data for over 750 samples from wells, qanats and springs in the area, collected from 1986 – 1997. The second comprises 328 analyses of Zayandeh River water, collected at six stations along the river during the period 1991-1998.

The evolution of the hydrochemical facies is described through the use of Piper and Stiff diagrams, while source rock deductions are made by means of the program WATEVAL (Hounslow, 1995). Spatial distribution of the EC values in the district is determined through application of Kriging methods and examples are given for temporal changes in EC at a few representative locations.

It is shown that the groundwater is of a limestone origin. However, because of frequent contacts with gypsum deposits, gypsum dissolution is strongly affecting the groundwater chemistry of most samples.

Furthermore, the analysis reveals that there is a natural groundwater flow northward which seeps into the Zayandeh Rud eventually. The irrigation return flow component is added to this. Although both flow components are small, they carry a significantly higher solute load than the Zayandeh Rud in this stretch of the river. Thus they change the river's chemical composition as it flows through the Lenjanat District.

Finally, it would appear that so-called mixing cell methods may be used to quantify natural groundwater seepage and irrigation return flow components, provided information is available with respect to their chemical composition. Groundwater flow and mass transport modelling would be of practical importance in the study of surface water-groundwater interactions along the Zayandeh Rud.

Introduction

The Esfahan hydrological province in central Iran is essentially a closed catchment with one perennial river, the Zayandeh Rud (Fig. 1a), which originates in the Zagros Mountains and ends 300 km downstream in the Gavkhuni Swamp, a highly saline salt pan. The Zayandeh River has provided the basis for centuries of important economic prosperity, including the establishment of Esfahan as a major city with over 2 million inhabitants. The region has traditionally been supported by irrigated agriculture, predominantly with river water, but also with groundwater tapped by qanats and hand dug wells. More recently, population growth and industrial development have increased the demand for water and at present both quantity and quality of the fresh water resources are under threat.

As one of the measures to regulate the flow of river water, Chadegan Dam was built in 1970 (Figs. 1a and 1b) and 1500 MCM per year is released on average (Salemi et al., 1999). It should be noted that 550 MCM of this amount results from trans-basin diversions. Two tunnels have been constructed leading water from the Kuhrang River Catchment into Chadegan Dam. A third tunnel is under construction. All water, however, originates from snowmelt and springs in the Zagros Mountains. The water quality of the river with respect to major anions and cations has been monitored regularly in 7 hydrometric stations along the Zayandeh Rud since 1991 (see Fig. 1b).

Groundwater plays an important role as an additional source of water. For example, the Esfahan water supply is augmented with groundwater in summer. In the irrigation command areas many farmers operate wells close to the irrigation channels. Further away from the irrigated areas, groundwater plays a dominant role in providing drinking water to small villages and small-scale irrigation schemes. Traditionally the groundwater was tapped by qanats and hand dug wells. However, in recent years many deep tube wells have been drilled. The groundwater has been monitored with respect to water level and quality in the entire Esfahan Province since the early 1980s.

In view of the large amount of hydrochemical data available it was decided to make an exploratory study of the Lenjanat subcatchment along the Zayandeh first (Fig. 1b). After a short description of the Lenjanat study area, the hydrochemical data set is discussed. Then an interpretation is made of the major ionic constituents of the groundwater and surface water. A variogram analysis of the EC values, followed by kriging, shows the spatial EC pattern in the area. Finally, a few examples are given of the observable hydrochemical trends in the area during the period 1986-1997.

Study area

The Lenjanat subcatchment (including the Ben Saman District to the west) is surrounded by NE-SW trending mountain ranges (see Fig. 1a). In the southern part these are the Zard Kuhbakhtiari Mountains. In the west the Ben Saman district is

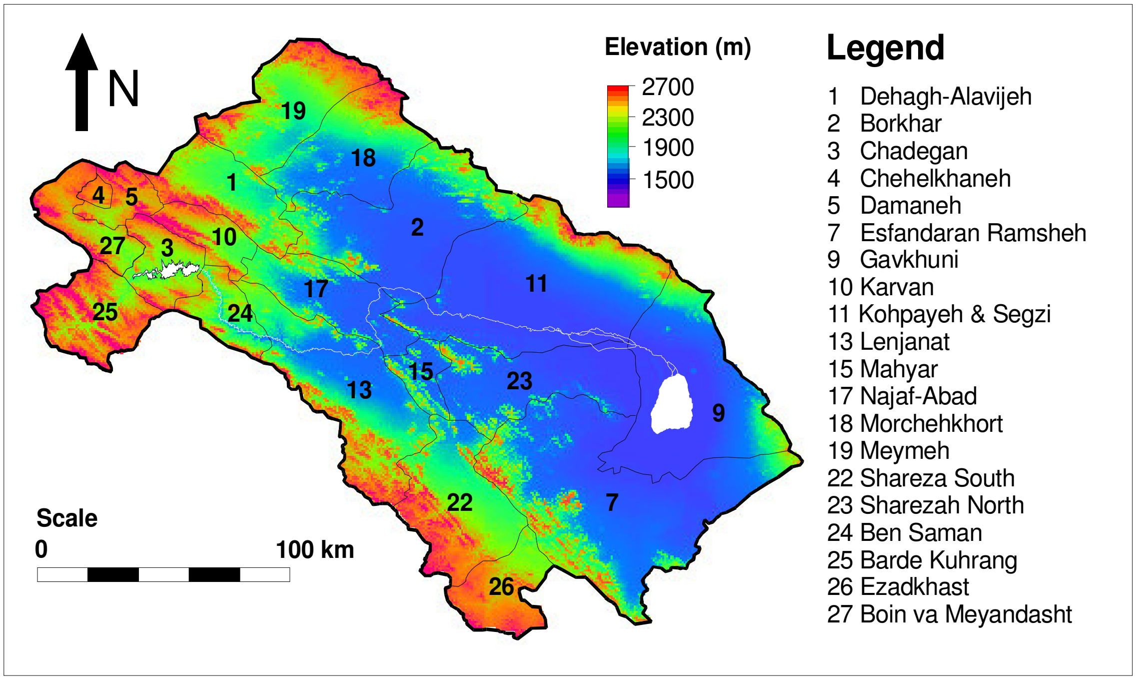

Fig. 1a Hydrological Districts in the Zayandeh Rud Basin. The elevations shown here on a 1x1 km grid, are derived from the digital chart of the world.

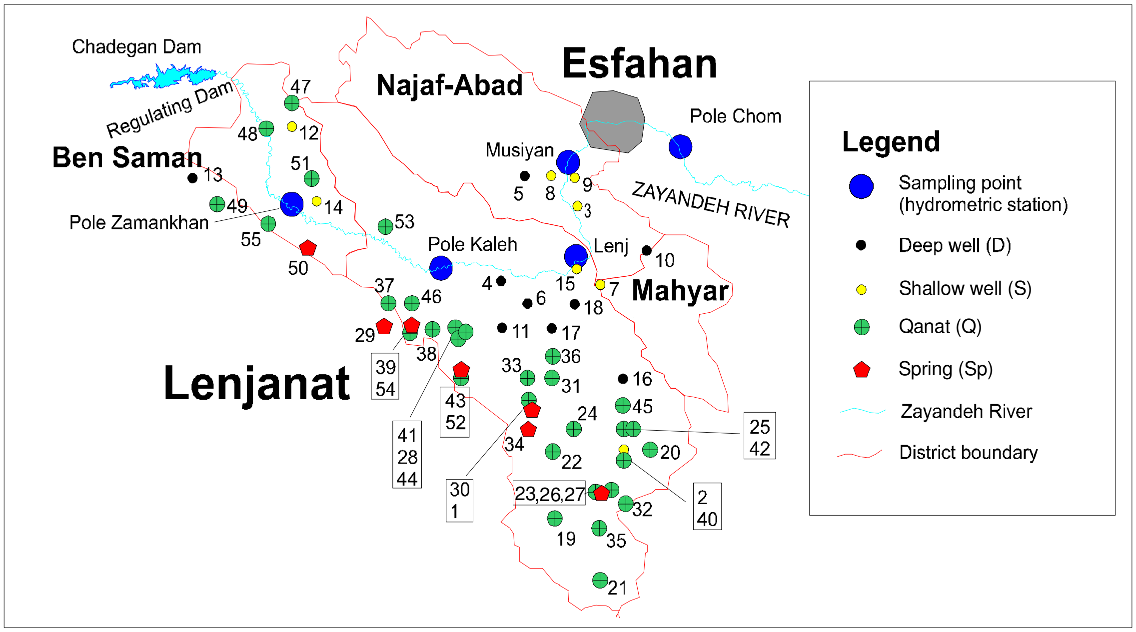

Fig. 1b Location map, showing wells,qanats and springs in the Lenjanat, Ben Saman and Najaf-Abad hydrological subcatchments, plotted on a 5x5 km grid. Also shown are the surface water sampling points.

bounded by the edge of the Zagros Mountain range, while another mountain range separates the Lenjanat catchment from the Najaf-Abad and Mahyar Districts. There are two gaps through which the Zayandeh Rud enters and leaves the Lenjanat District. In the west there is a gap in the Zagros Mountain range, which has been used to build the Chadegan Dam. In the north there is a much wider break in the mountains through which the Zayandeh Rud flows north towards Esfahan. This is also the point where a large diversion dam has been built to supply the main Nekouabad irrigation canals. The elevations in the Lenjanat plains vary from about 2000m to 1600m above sea level, while the mountains rise 800 to 1000m above the surrounding plains. Near Chadegan Dam the elevation of the Zayande Rud is about 2000 m, whereas it is about 1650m near the northern outlet.

Because the groundwater contour lines follow the topography, the groundwater flows towards the Zayandeh Rud. For example, south of the Zayande Rud the natural groundwater flow direction is generally towards the north, provided suitable aquifer structures are present of course. Fig. 1b shows the sampled wells, qanats and springs in the area. In general their coordinates are recorded on a 5x5 km^2 grid. For this reason some wells are plotted on the same grid position. Sometimes maps are available with well, qanat and spring positions plotted more precisely, but this is not usually the case.

Fig 1b also indicates that some wells (3, 5, 8 and 9) are located in the Najaf-Abad district, inside the Nekouabad irrigation scheme, despite the fact that they were archived in the Lenjanat records. Well 10 lies close to the boundary between the Najaf-Abad and Mahyar Districts. Finally, the Lenjanat and Ben Saman Districts have been combined in this analysis because there does not appear to be a clear hydrological boundary between these two districts.

Data sets

Two data sets, both made available by the Ministry of Energy (ERWO), were used to assess the hydrochemistry of the area,:

1. A set of over 750 analyses collected from 55 wells, qanats and springs in the period from 1986 to 1997 (see Fig 1b). The number of analyses per sampling point is 14 on average, ranging from 2 to 21. For reasons of space only the average data for each well are given in Table 1.

2. A set of 328 analyses for samples collected at 6 hydrometric stations in the period from 1991 to 1998. The following stations are included in this analysis (Fig. 1b): Pole Zamankhan, Pole Kaleh, Lenj, Pole Chom, Musiyan and Varzaneh. The average data for these stations are shown in Table 2.

The samples of both the groundwater and the surface water were all analyzed for: pH, EC, Cl^-, CO_3^-, HCO_3^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, K^+, SAR and %Na.

Quality checks

The samples were checked in four ways (Hounslow, 1995, Appelo and Postma, 1996):

- EC/100 (EC in µS/cm) was plotted against the sum of the anions (in meq/l). For low concentration solutions this should yield a straight line.

- EC/100 (EC in µS/cm) was plotted against the sum of the cations (in meq/l). Again this should give a straight line.

- The sum of the anions should be equal to the sum of the cations. The error is usually expressed in % as: (Σcations-Σanions)/(Σcations+Σanions) x100.

- The presence of time series of observations makes it possible to check for outliers.

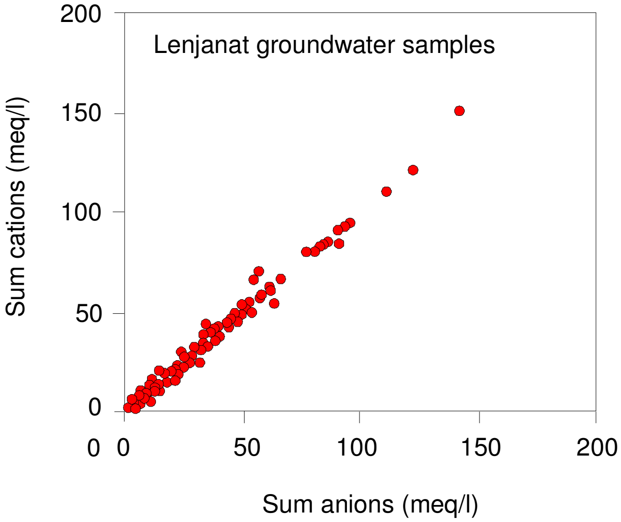

Fig. 2 Scatter diagram of the sum of the anions against the sum of the cations (groundwater samples Lenjanat).

Using these four methods the data was carefully examined, and obvious errors were corrected. The last outliers were then removed from the set. Fig. 2 shows for the resulting groundwater data set, a scatter diagram of the sum of the anions against the sum of the cations. The average error is 0.95% with a minimum and maximum error ranging from 0 to 15% respectively, while the standard deviation is 2.1. The average error in the surface water data set is 0.78%, with maximum and minimum ranging from 0 to 9.0%.

Hydrochemical facies

Because the Zayandeh Rud flows through the Lenjanat District some aspects of the surface water hydrochemistry will be discussed first, followed by the analysis of the groundwater samples.

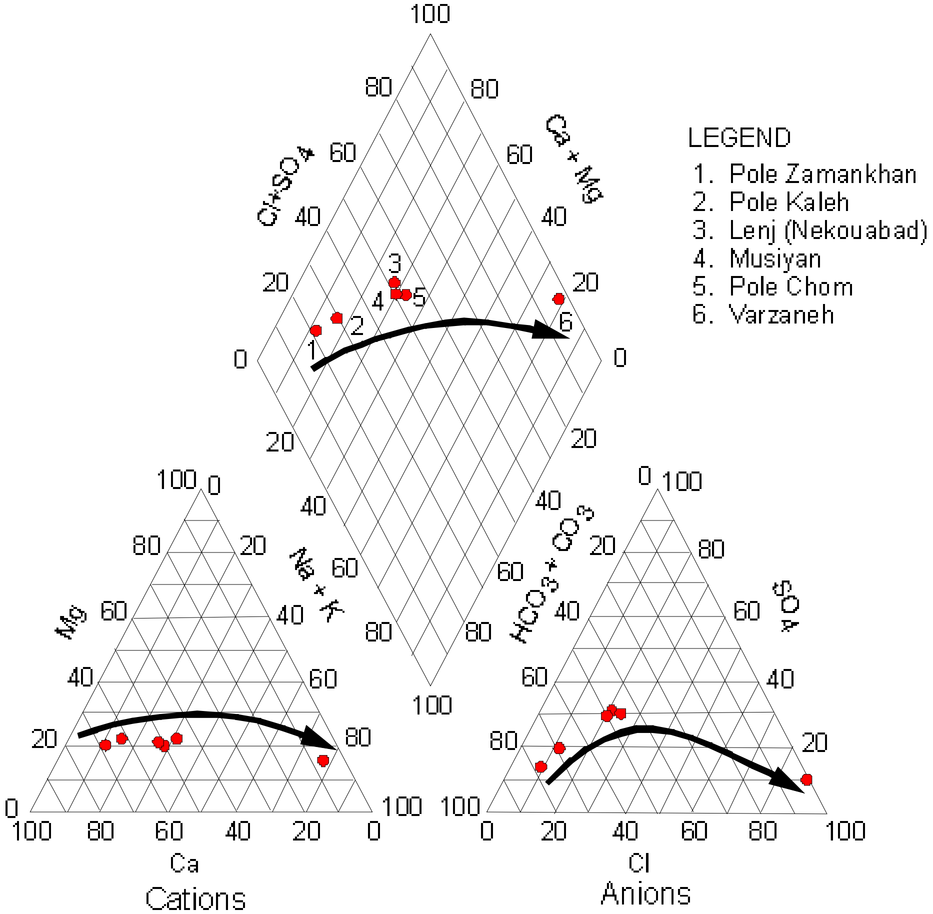

Fig. 3 Piper diagram showing chemical evolution of the Zayande Rud water from Pole Zamankhan towards Varzaneh (averages over the period 1989 - 1997).

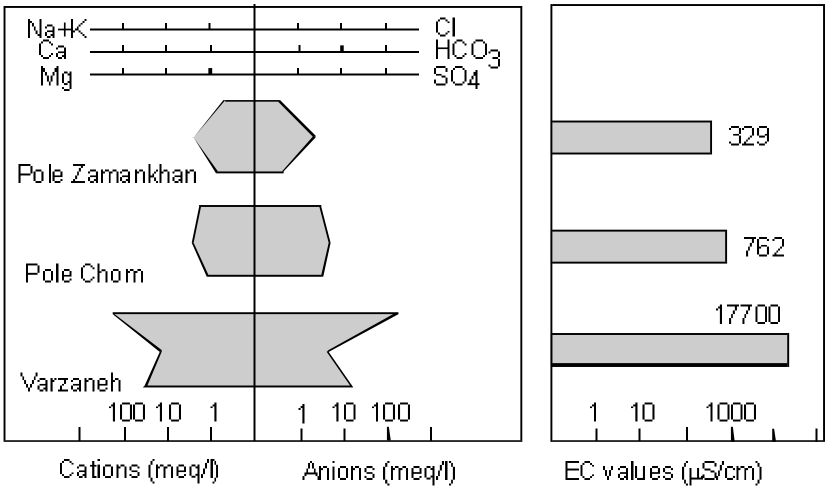

Fig. 4 Stiff diagrams and EC values of average river water chemical composition at three stations along the Zayandeh Rud (1989-1997).

Surface water

Kalbasi and Mousavi (1995) conducted a study on water quality fluctuations using samples from the Zayandeh Rud, collected at 15 stations during the period from 1988-1994. Apart from pH, EC, major anions and cations, the samples were also analyzed for N, P, and heavy metals. Their study concentrated on the hydrochemistry of the Zayande Rud downstream of Esfahan. The dataset used here, was made available by the Ministry of Power and contains data collected for 6 stations from 1991 – 1998. The samples were analyzed for pH, EC, major anions and major cations. Appendix 1 (Table 2) gives the averages, maxima, minima and standard deviations for these stations: Pole Zamankhan, Pole Kaleh, Lenj, Musiya, Pole Chom and Varzaneh. The present analysis is therefore complementary to the earlier work by Kalbasi and Mousavi (1995).

Fig. 4 shows the average EC values for three stations: Pole Zamankhan, Pole Chom and Varzaneh. From the first station (close to Chadegan Dam) to the second (dowstream of Esfahan) there is an increase in EC from 329 to 762 µS/cm. However, from the second to the third station (close to Gavkhuni Swamp) the EC increases by more then a factor 20. Therefore the largest increase in EC occurs well beyond Esfahan. While flowing through the Lenjanat District the electrical conductivity of the Zayandeh river water increases only from 300 to about 600 µS/cm.

The changing ionic composition of the Zayandeh water is shown in a Piper diagram (Fig. 3) and in three Stiff diagrams (Fig. 4). The Piper diagram clearly shows that the initial composition plots as a Ca^{2+}-$HCO3^{-}$ type water, as could be expected in a limestone/dolomite environment with relatively high recharge. The Stiff diagram for Pole Zamankhan shows the typical diamond shape of this type of water. Further downstream, past Esfahan at Pole Chom, the ionic concentrations of sodium, chloride, magnesium and sulphate have increased relative to those of calcium and bicarbonate. This leads to a more rectangular shape of the Stiff diagram. The Piper diagram shows that the further the sampling points are downstream of Chadegan Dam, the further they plot to the right, following the direction of the three arrows towards the right hand corners of the rhombus and the two triangles. Finally, in Varzaneh the ionic composition of the water is dominated by Na^{+}, K^{+}, Cl^{-} and SO_4^{2-} and the points are plotted in the far right corners of the triangles and rhombus. The Stiff diagram for Varzaneh attains the typical hourglass shape, characterizing this highly saline brine. The convex shape of the arrows in the Piper diagram suggests that cation exchange processes are involved. Hence interaction between surface water and groundwater needs to be examined.

Groundwater

The ionic content and associated hydrochemical changes of the groundwater in the Lenjanat District is less easily understood, as is illustrated by Fig 5. The points are scattered over the diagram, while the Stiff diagrams show the presence of different types of water. The program WATEVAL (Hounslow, 1995) was used to calculate the Langelier saturation index for calcite and several other indices such as $Na^{+}/(Na^{+}+Cl^{-})$, $Ca^{2+}/(Ca^{2+}+SO_4^{2-})$, $Mg^{2+}/(Ca^{2+}+Mg^{2+})$, $(Ca^{2+}+Mg^{2+})/SO_4^{2-}$ and HCO_3^{-}/(sum anions).

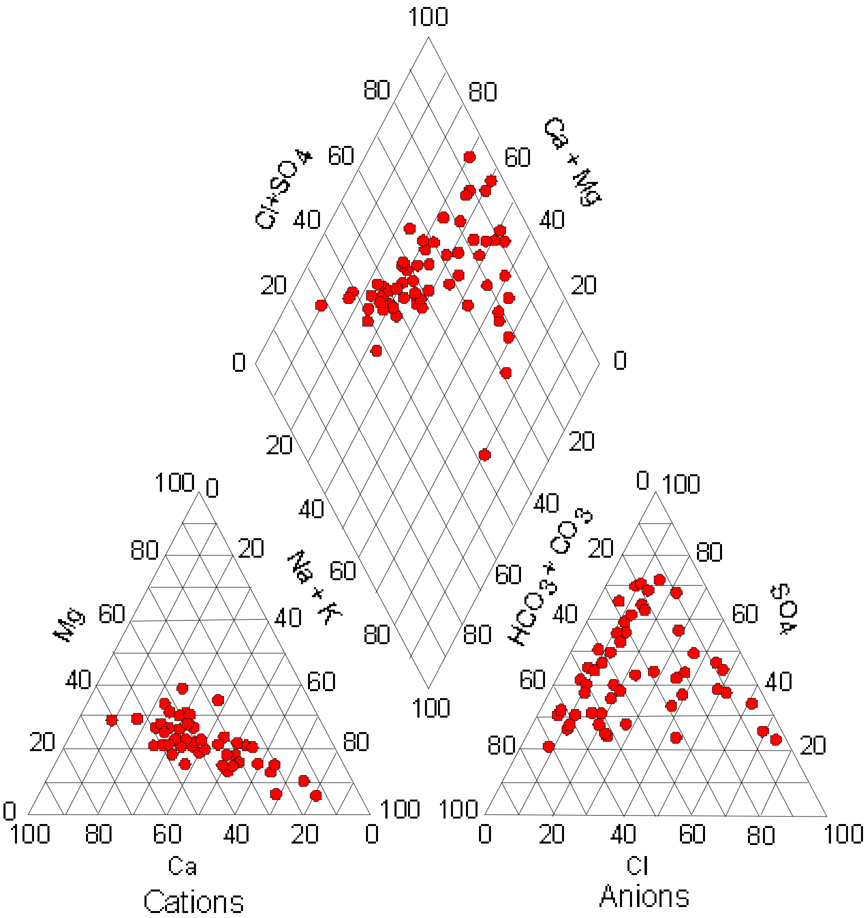

Fig. 5 Piper diagram showing average chemical composition of 55 wells in the Lenjanat and Ben Saman hydrological districts (1986-1998).1

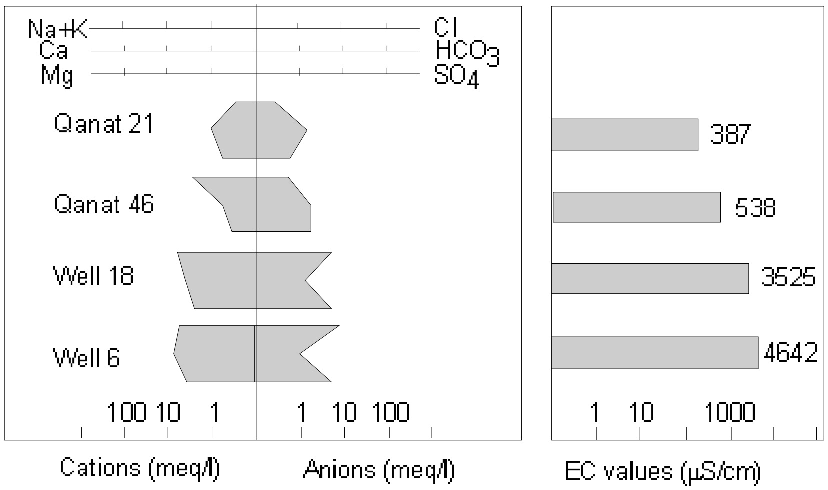

Fig. 6 Stiff diagrams and EC values of average groundwater composition in four wells of the Lenjanat Districts (1986 -1997).

Table 1 Source rock deductions as determined with WATEVAL (Hounslow, 1995)

				conclusions
1	Langelier index	0.16	average	**slightly oversaturated with**
		0.14	stand.dev.	**respect to calcite**
2	Halite $Na^+/(Na^++Cl^-)$	11%	=0.5	**sodium source other than halite:**
		78%	>0.5	**some ion exchange**
		11%	<0.5	**no reported diapirs in area: no halite dissolution**
3	$Mg^{2+}/(Ca^{2+}+Mg^{2+})$	100%	<0.5	**limestone/dolomite weathering**
4	$Ca^{2+}/(Ca^{2+}+SO_4^{2-})$	27%	=0.5	**gypsum**
		40%	<0.5	**Ca removal: ion exchange/calcite precipitation**
		33%	>0.5	**Ca source other than gypsum: carbonates likely**
5	$(Ca^{2+}+Mg^{2+})/SO_4^{2-}$	20%	>0.8 and <1.2	**dedolomitization only locally indicated**
		80%	<0.8 and >1.2	
6	HCO_3^-/sum anions	100%	<0.8	**gypsum dissolution indicated in most cases**
		generally	high sulphate	

Table 1 summarizes the conclusions of the WATEVAL calculations. The groundwater is slightly oversaturated with respect to calcium, indicating that calcite precipitation may take place. The $Na^+/(Na^++Cl^-)$ ratio is greater than 0.5 in 78% of the cases, suggesting that ion exchange place where Na^+ is replacing Ca^{2+} in the clay minerals, while reverse ion exchange where Ca^{2+} is replacing the Na^+ (natural softening) is indicated in only 11 % of the cases. No diapirs (salt domes) have been reported in the area and therefore halite dissolution appears unlikely.

The $Mg^{2+}/(Ca^{2+}+Mg^{2+})$ ratio indicates limestone/dolomite weathering in all cases. The $Ca^{2+}/(Ca^{2+}+SO_4^{2-})$ ratio suggests gypsum in 27 % of the cases, Ca2+ removal due to precipitation or ion exchange in 40% and carbonate sources other than gypsum in 33% of the cases. If the $(Ca^{2+}+Mg^{2+})/SO_4^{2-}$ index is between 0.8 and 1.2 dedolomitization is likely to occur. Because only about 20% of the values lie within this range, this process is only locally indicated. Finally, the ratio HCO_3^-/(sum anions) is less than 0.8 in all cases and because sulphate is generally high, gypsum dissolution is strongly indicated.

In summary, the hydrochemistry of the Lenjanat District points clearly at groundwater recharge in a carbonate rock environment, in this case the southern mountain range. On its way northward towards the Zayandeh Rud, the groundwater may come in contact with gypsum deposits. If it does, gypsum is dissolved and water quality deteriorates. This is in line with the findings of Raeisi (1995) who reported that groundwater in carbonate terrain will deteriorate very quickly if it comes in contact with anhydrite or gypsum deposits.

The Piper diagram also reveals this pattern. Fresh Ca^{2+}-$HCO3^-$ water from the southern mountain range is plotted in the left corner of the rhombus. As the groundwater flows northward, it may come into contact with gypsum deposits. Its Ca^{2+} and SO_4^{2-} content then increases and the composition plots more to the right in the Piper diagram.

The scattered distribution in the anion triangle may be explained through the fact that gypsum deposits are not equally distributed over the area. If large quantities of gypsum are dissolved the evolution will be towards the top of the anion triangle, whereas if the presence of gypsum is less strong the groundwater evolution will be more towards the right hand apex of the anion triangle with relatively higher Cl^- content.

With regard to the origin of gypsum, Toomanian et al. (1999) reported that gypsum deposits occur in shales and limestones of Cretaceous Age which are found to the South and North of the Lenjanat Districts. Moreover, gypsum is found abundantly in the alluvial fans emanating from the mountains. Gypsiferous soils are limited to the range between the mountains and the lower alluvial plain of the Zayandeh.

The variety in Stiff diagrams (Fig. 6) may be explained similarly. The diagram of qanat 21 (see also Fig. 1b and 8) has the typical diamond shape of groundwater in a limestone environment, whereas wells 18 and 6 show increased chloride and sulphate concentrations with relatively low bicarbonate content. The Stiff diagram of qanat 46 represents an isolated case, deviating from the others because of its high (Na^++K^+) content, and the groundwater of this area should be classified as an alkali-carbonate type of water.

Geostatistics

The spatial distribution of the EC values in the Lenjanat District was determined by means of Kriging. This analysis requires two steps (see e.g. Isaaks and Srivastava, 1989):

1. Determine the spatial correlation in the dataset

The spatial correlation between EC values at different locations has to be found through calculation of so-called semi-variograms, where the semi-variance γ is plotted as a function of the distance h between water sampling points:

$$\gamma(h) = (1/2n) \Sigma [z(x) - z(x+h)]^2$$

where z is the EC value at location x and n is the number of pairs of sampling points in a certain distance interval. The object of this analysis is to find a theoretical model that fits the observations. The model produces a <u>sill</u> (which is about equal to the variance of the data set), the <u>range</u> (the distance at which there is no longer any spatial correlation) and the nugget (the random variation between values at sampling sites which are very close together). Fig. 7 illustrates these concepts in a diagram.

2. Kriging

Once the variogram model has been established, it is used as the spatial correlation model for the Kriging process. This method can be understood in simple terms as the best statistical method for interpolation and contouring.

In the present case there is an additional complication, because the x- and y-coordinates of the water sampling positions are only accurate to 5 km, because they were recorded on a 5x5 km^2 grid, as mentioned earlier. However, with proper caution Kriging may still be used and the results are shown in Figs 8 and 9. A gaussian model with nugget $4\text{x}10^4$ $\mu S^2/cm^2$, sill $1.3\text{x}10^6$ $\mu S^2/cm^2$ and range 40 km was found to fit the data best (Fig. 9). For Kriging purposes the semi-variogram model is only used for distances between 0 and 20 km, so the deviation of the variogram from the model for distance values above 40 km is not important. Finally, Kriging was implemented through ILWIS 2.2 and the resulting map is shown in Fig. 8.

A clear picture emerges where groundwater recharge predominantly takes place in the southern mountain range, and where the groundwater becomes more mineralized as it flows northward. The high EC values around wells 11, 6 and 18 may have three additional causes:

1. The presence of point pollution sources, for example, industry.

2. The extensive use of groundwater for irrigation in the area around the wells.

3. It may be possible that the deep wells are drilled in a deeper more saline aquifer.

However, it requires further work to identify the exact causes, because the well positions are not accurate enough at present and field inspections are required.

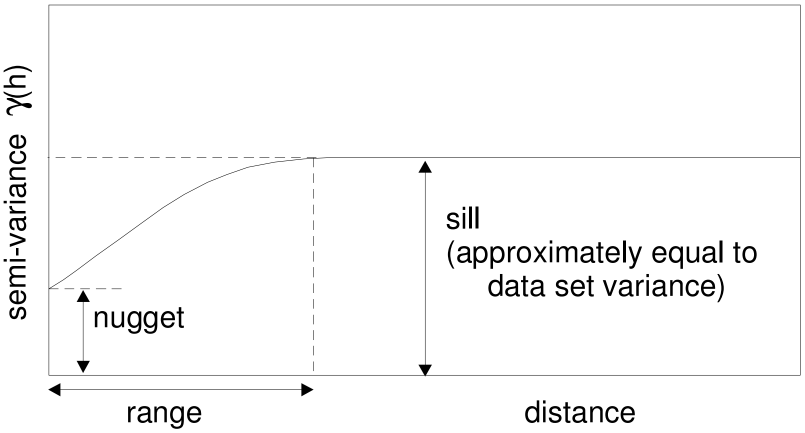

Fig. 7 Semi-variogram characteristics

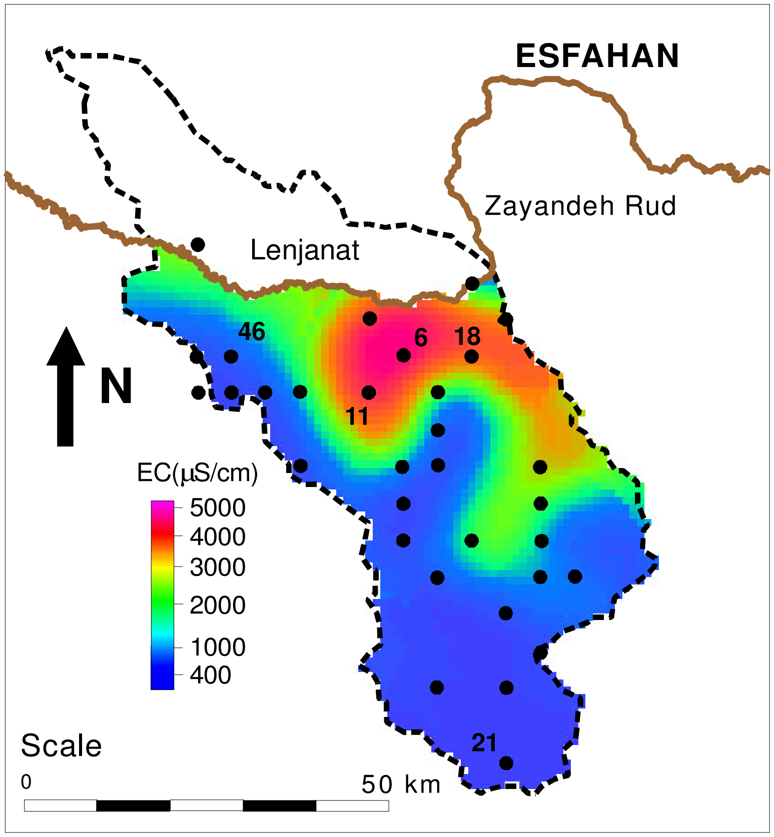

Fig. 8 Kriged map of the EC values in the southern part of Lenjanat District below the Zayandeh Rud, while the variogram model is shown in Fig. 9. A search radius of 20 km was used with pixel size 1 km.

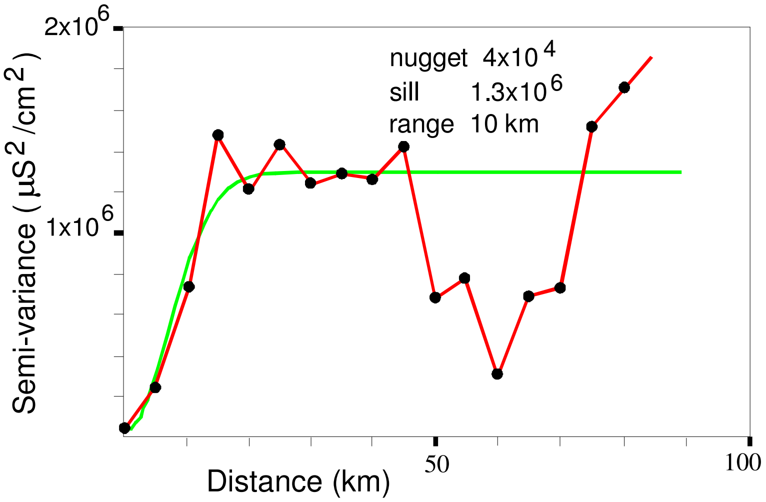

Fig. 9 Semi-variogram of EC values in the southern part of the Lenjanat District south of the Zayande Rud.

Trend Analysis

A few representative examples are illustrated in Fig. 10 and described as follows:

Deep well 11 (see also Fig. 8) has tripled its EC contents over the past 10 years. This rise cannot be explained from natural groundwater flow conditions. As mentioned before, two explanations seem possible. First, the well could be influenced by an industry point pollution source. Second there could be substantial irrigation by groundwater in the area. However, further study and field work are required to explain this rise. Well 10 also shows a substantial rise in EC with time. Because this well, however, lies outside the Lenjanat District near the boundary between the Najaf-Abad and Mahyar Districts it is left out of the present discussion.

Deep well 18, which also lies in the zone of high EC values, shows fluctuating but decreasing EC values with time. The fluctuations seem again too large to be explained by natural groundwater flow conditions. It appears that irrigation by river water takes place in the vicinity of this well.

Shallow well 9 lies outside the Lenjanat District in the Najaf-Abad District and well inside the Nekouabad irrigation command area. The graph shows that EC values around this well have been reduced significantly since 1988, most likely as a result of irrigation.

Finally, the EC fluctuations in Qanat 19 are representative of the natural EC fluctuations in the other qanats and springs of the Lenjanat area. These natural fluctuations are in the range of 200 µS/cm. There is no significant trend with time.

Analysis and Discussion

Using the chemical data that was made available by the Ministry of Energy (Esfahan Regional Water Organization), it was possible to describe the change in hydrochemical facies of both surface water and groundwater. The Zayandeh Rud water originates in a limestone environment and as the water passes through the system towards Gavkhuni Swamp, its composition evolves toward highly saline brine. While it flows through the Lenjanat District, however, its EC values change by a factor 2 only: from about 300 to 600 µS/cm.

The groundwater originates most likely in the limestone environment of the southern mountain range with an EC of about 400 µS/cm. As it flows northward, it becomes more mineralized and its EC is rising to about 2000 µS/cm, especially when the groundwater comes in contact with gypsum deposits. Closer to the Zayandeh Rud, the electrical conductivity may be as high as 6000 µS/cm. The time trends suggest that this is caused either by industrial pollution or by extensive irrigation with groundwater. Water from the deeper wells near the Zayandeh may be in contact with deeper more saline aquifers, in which case sampling would have been biased. However, an active unconfined aquifer system is indicated because of the fairly large fluctuations in EC

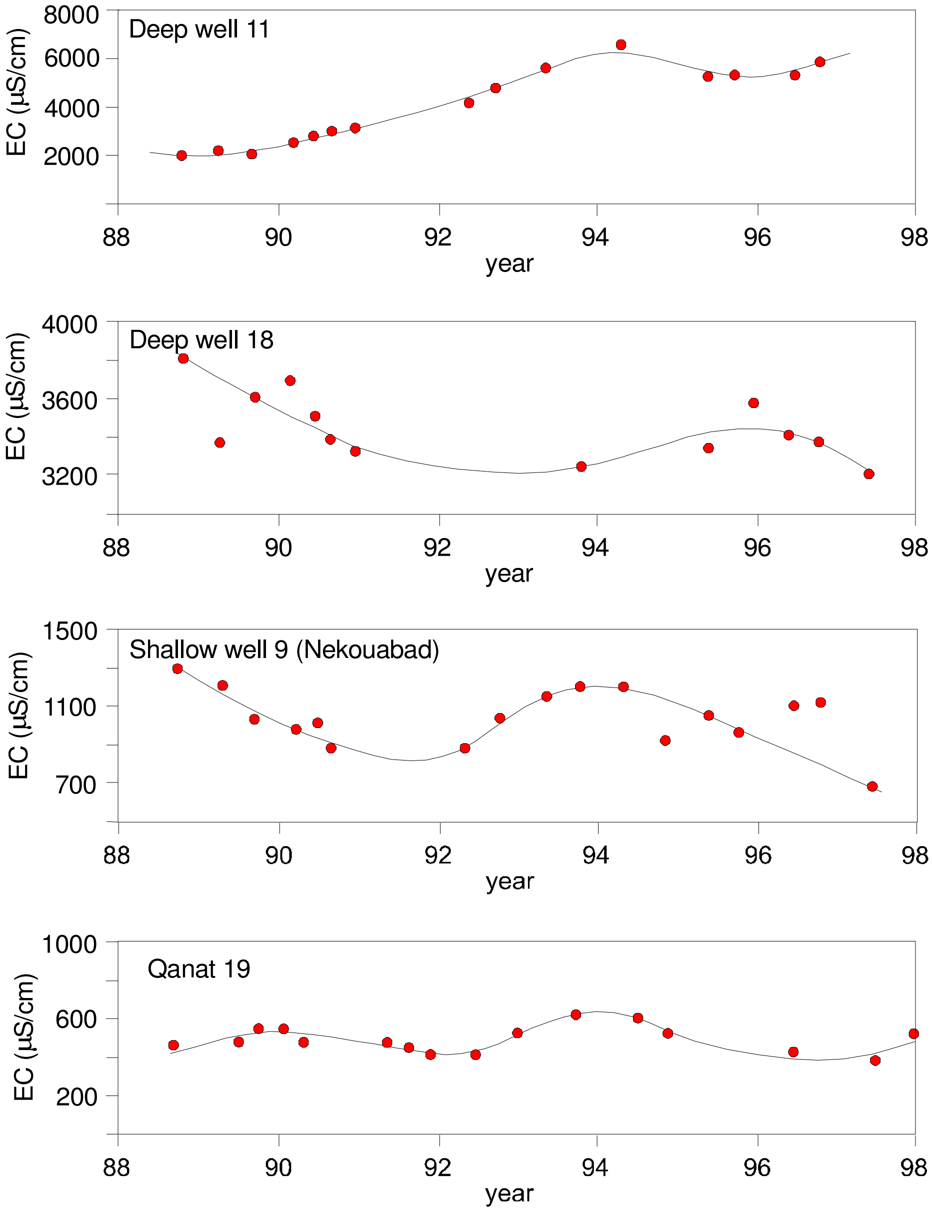

Fig. 10 Long-term trends in the EC of the four sampling points: 11, 18, 9 and 19

values with time. Field work and further study would be required to resolve this issue, as discussed in the main text.

Because it seems likely that both groundwater and irrigation return flow reach the Zayandeh Rud and then mix with the fresh river water, it is instructive to make a simple conceptual model of the situation. Consider the stretch of river between Pole Kaleh and Lenj (Nekouabad) as a single cell, as was discussed in Droogers et al. (2000). Five components can be distinguished (as illustrated in Fig. 11):

- River inflow I with concentration c_i
- River outflow O at Lenj with concentration c_o (combining the flow through the river with the irrigation offtake at the diversion weir)
- Groundwater seepage S with concentration c_s
- Irrigation and urban abstraction G with concentration c_g (according to Droogers et al., 2000, this is about 9.5 m^3/s on average)
- Return flow R with concentration c_r (10% salt sequestration is assumed)

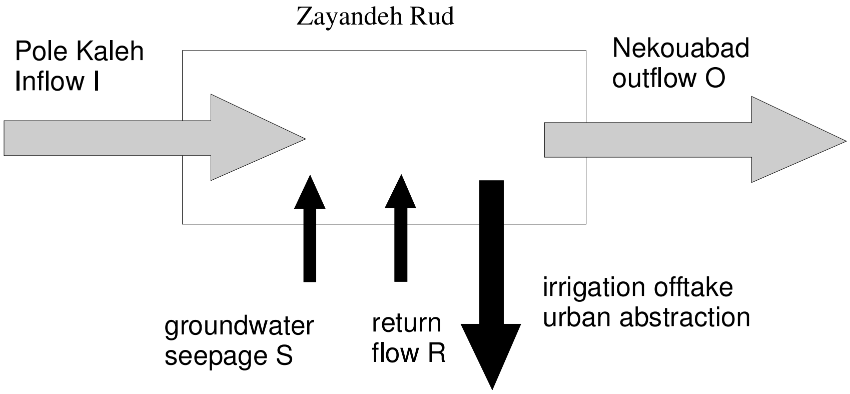

Fig. 11 Conceptual mixing model for the Zayandeh river stretch from Pole Kaleh to Nekouabad.

The indicative values for flow rates and concentrations are summarized in Table 2.

Table 2 Concentrations and flow rates of the five component conceptual model (the influence of precipitation and evaporation are left out in this example).

Flow component	Q (m^3/s)	EC (µS/cm)	TDS (g/m^3)
Pole Kaleh inflow I	54.0	366	256
Nekouabad outflow O	50.0	575	403
Groundwater seepage S	?	3000	2100
Irrigation/urban G	9.5	471	330
Return flow R	?	2120	1484

There are two balance equations for the 5 components, resulting from water and solute mass balance conservation. They may be written as:

$$I+S+R=G+O$$

$$C_iI+c_sS+c_rR=c_gG+c_oO$$

Solution yields the following values for return flow R and groundwater seepage S: R=3.4 m^3/s and S=2.1 m^3/s. Thus, the irrigation return flow percentage becomes: 100*(R/G)=36%. It would not be correct to calculate the return flow percentage as 100*(R+S)/G=58%. Note that in case the concentrations of S and R are equal, it is no longer possible to solve the equations. The two components S and R can then no longer be distuiguished as separate components.

General mixing cell methods have been developed that not only take into account the conservation of TDS, but also the conservation of individual ionic species, provided these are conservative. This means that they should not be subject to chemical reactions, such as precipitation. Usually this leads to overdetermined sets of equations, where the number of equations exceeds the number of unknown parameters. These sets of equations can be solved by standard mathematical methods.

Finally, the example given here, illustrates the importance of considering the groundwater outflow component on the solute balance of the Zayandeh Rud. Groundwater flow and mass transport modelling of the Lenjanat District would lead to direct evaluation of the groundwater outflow component and its EC value. The modelling would thus be of direct practical importance for improving the estimates of return flow.

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APPENDIX 1

Table 1 Groundwater chemistry data 55 boreholes in the Lenjanat, Ben Saman and Najaf-Abad Districts (averages over the period 1986-1997)

No	UTMx	UTMy	type	num sam	pH	EC25C muS/cm	TDS mg/l	Cl mg/l	CO3	HCO3 mg/l	S04 mg/l	suman meq/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	sumca meq/l	EC/100 xx	error %
1	540000	3555000	SP	5	7.96	446	273	30.4	0.00	147.56	68.4	4.70	42.5	15.89	29.64	0.32	4.72	4.46	0.27
2	560000	3545000	S	13	7.97	1104	732	46.3	0.00	179.98	332.0	11.17	71.1	31.21	116.06	1.27	11.19	11.04	0.23
3	550000	3595000	S	14	7.70	1570	1091	217.4	0.00	269.74	266.6	16.11	121.7	46.82	143.48	1.34	16.19	15.70	0.48
4	535000	3580000	D	17	7.77	3400	2370	541.6	0.00	169.84	798.5	34.70	232.1	68.08	407.76	1.25	34.94	34.00	2.37
5	540000	3600000	D	10	7.75	1934	1353	284.0	0.00	297.73	370.8	20.62	147.9	51.77	192.89	3.24	20.11	19.34	1.91
6	540000	3575000	D	17	7.69	4642	3250	1069.4	0.00	117.71	821.6	49.21	476.0	119.17	362.72	1.91	49.39	46.42	0.17
7	555000	3580000	S	13	7.70	2435	1704	254.3	0.00	236.54	699.6	25.63	108.6	47.06	374.51	2.04	25.62	24.35	1.17
8	545000	3600000	S	2	7.65	717	466	49.6	0.00	219.64	91.5	6.91	63.1	24.32	39.68	1.17	6.90	7.17	0.02
9	550000	3600000	S	17	7.74	1046	699	104.1	0.00	284.36	147.0	10.66	79.2	40.96	76.06	1.24	10.66	10.46	0.24
10	565000	3585000	D	15	7.68	8798	6122	2478.2	0.00	89.45	1093.9	94.16	712.0	238.10	902.83	3.59	94.46	87.98	0.67
11	535000	3570000	D	15	7.69	4095	2856	1023.8	0.00	133.41	513.8	41.77	346.2	103.85	401.61	1.69	43.32	40.95	1.27
12	490000	3610000	S	2	7.85	563	366	44.3	0.00	192.18	98.5	6.45	64.1	17.02	42.32	0.39	6.45	5.63	0.01
13	470000	3600000	D	2	8.30	703	600	47.9	0.00	192.18	144.8	7.52	58.1	18.24	60.03	0.21	7.02	7.03	2.42
14	495000	3595000	S	4	7.75	3380	2366	308.5	0.00	198.28	1206.8	37.09	253.0	66.27	436.43	0.98	37.08	33.80	0.02
15	550000	3585000	S	3	7.60	1004	688	86.0	0.00	305.05	113.5	9.79	90.9	26.75	69.77	1.17	9.80	10.04	0.05
16	560000	3560000	D	14	7.86	2663	1763	503.8	0.00	171.70	494.1	27.32	143.7	75.04	319.55	1.51	27.27	26.63	0.26
17	545000	3570000	D	15	7.83	1991	1384	361.5	0.00	139.91	383.4	20.48	167.3	57.47	166.75	3.79	20.42	19.91	0.56
18	550000	3575000	D	15	7.78	3525	2470	618.0	0.00	175.52	796.8	36.91	218.6	77.82	460.52	1.65	37.37	35.25	0.85
19	545000	3530000	Q	17	7.81	495	317	20.6	0.00	192.17	63.5	5.05	53.9	18.42	19.70	0.71	5.08	4.95	0.35
20	565000	3545000	Q	16	7.87	826	511	69.4	0.00	173.45	180.2	8.55	72.3	33.37	47.45	1.32	8.44	8.26	1.11
21	555000	3520000	Q	16	7.83	387	243	11.3	0.00	173.97	40.4	4.01	46.5	13.97	9.26	0.43	3.88	3.87	2.29
22	545000	3545000	Q	15	7.89	944	621	48.2	0.00	178.97	258.1	9.67	61.8	28.52	100.10	0.81	9.80	9.44	0.99
23	555000	3540000	SP	17	7.84	745	484	32.6	0.00	151.87	195.9	7.49	61.1	21.16	60.78	1.03	7.46	7.45	0.61
24	550000	3550000	Q	18	7.93	1962	1229	108.9	0.00	162.39	697.0	20.25	95.5	39.66	272.40	1.04	19.89	19.62	1.13
25	560000	3550000	Q	18	7.92	902	586	89.1	0.00	161.30	194.9	9.22	70.2	30.75	70.68	1.28	9.14	9.02	1.40
26	555000	3540000	Q	18	7.89	733	484	31.5	0.00	147.46	199.7	7.47	61.4	23.56	53.65	0.85	7.36	7.33	1.25
27	555000	3540000	Q	17	7.94	1088	719	46.5	0.00	191.24	320.2	11.12	54.8	30.72	137.62	1.33	11.28	10.88	0.76
28	525000	3570000	Q	17	7.85	1741	1198	97.3	0.00	244.80	562.5	18.48	78.3	29.85	273.71	1.29	18.29	17.41	0.55
29	510000	3570000	SP	17	7.97	679	399	104.2	0.00	129.29	79.4	6.71	60.9	20.19	46.01	0.68	6.72	6.79	1.25
30	540000	3555000	Q	19	7.83	565	367	30.8	0.00	185.83	87.8	5.74	56.1	19.34	30.90	0.71	5.75	5.65	2.04

APPENDIX 1
Table 1 (continued)

No	UTMx	UTMy	type	num samples	pH	EC25C muS/cm	TDS mg/l	Cl mg/l	CO3	HCO3 mg/l	S04 mg/l	suman meq/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	sumca meq/l	EC/100 xx	error %
31	545000	3560000	Q	19	7.88	624	407	41.5	0.00	168.88	111.0	6.25	53.2	17.58	49.50	0.71	6.27	6.24	1.70
32	560000	3535000	Q	19	7.86	672	436	55.6	0.00	219.63	87.1	6.98	59.0	28.99	36.43	0.97	6.93	6.72	1.46
33	540000	3560000	Q	17	7.81	1652	1243	64.5	0.00	191.26	599.3	17.44	110.7	41.06	196.05	0.86	17.45	16.52	0.76
34	540000	3550000	SP	19	7.86	615	377	45.0	0.00	156.08	115.0	6.23	55.4	16.69	46.88	0.60	6.19	6.15	0.45
35	555000	3530000	Q	19	7.86	497	322	20.5	0.00	195.23	69.6	5.23	55.7	18.65	19.55	0.71	5.18	4.97	1.19
36	545000	3565000	Q	18	7.88	1097	742	139.2	0.67	147.02	226.9	11.09	93.3	32.83	84.61	0.92	11.06	10.97	0.63
37	510000	3575000	Q	21	7.89	659	430	24.6	3.29	200.27	132.9	6.85	63.2	21.75	41.57	0.57	6.76	6.59	1.18
38	520000	3570000	Q	16	7.88	754	492	29.0	0.38	175.36	181.8	7.49	68.9	14.60	65.63	0.57	7.51	7.54	0.64
39	515000	3570000	SP	18	8.02	454	296	18.3	0.33	162.15	70.4	4.65	49.1	12.77	27.26	0.60	4.70	4.54	0.74
40	560000	3545000	Q	18	7.77	1555	1005	79.1	0.00	167.76	537.2	16.17	105.3	44.97	165.46	1.32	16.18	15.55	0.46
41	525000	3570000	Q	20	8.10	1348	917	35.4	0.00	224.07	435.9	13.75	38.3	17.86	237.75	0.53	13.73	13.48	0.79
42	560000	3550000	Q	21	7.93	1435	912	55.9	0.00	183.59	493.7	14.87	59.4	29.99	215.65	0.84	14.83	14.35	1.05
43	525000	3560000	Q	6	8.10	568	369	26.6	0.00	158.62	139.6	6.26	48.1	23.30	39.80	1.89	6.09	5.68	1.25
44	525000	3570000	Q	5	8.00	1276	893	68.3	0.00	183.03	427.7	13.84	65.6	12.15	219.65	0.49	13.84	12.76	0.03
45	560000	3555000	Q	21	7.89	2047	1426	278.5	0.57	245.94	451.5	21.31	111.9	92.29	180.61	2.26	21.07	20.47	1.00
46	515000	3575000	Q	19	8.21	841	538	28.5	1.33	240.18	186.8	8.68	22.4	6.42	162.53	0.40	8.72	8.41	1.17
47	490000	3615000	Q	3	8.20	565	367	18.9	0.00	162.69	162.0	6.58	51.4	21.27	42.93	5.46	6.32	5.65	3.04
48	485000	3610000	Q	2	8.30	434	282	14.2	0.00	155.17	99.0	5.01	41.1	13.38	36.65	0.41	4.75	4.34	2.77
49	475000	3595000	Q	2	8.30	439	285	14.2	0.00	213.54	89.3	5.76	36.1	25.54	26.57	8.00	5.26	4.39	4.15
50	495000	3585000	SP	2	8.30	408	265	10.6	0.00	173.88	67.1	4.55	38.1	11.55	31.05	2.15	4.26	4.08	3.34
51	495000	3600000	Q	6	8.17	1275	884	43.7	0.00	163.75	447.7	13.25	62.9	33.23	165.41	1.05	13.09	12.75	0.95
52	525000	3560000	SP	16	8.03	683	444	31.0	0.00	160.61	166.9	6.98	58.2	22.49	49.53	0.83	6.93	6.83	0.63
53	510000	3590000	Q	19	7.65	2325	1539	317.3	0.00	197.95	589.1	24.47	164.7	51.85	275.54	2.23	24.52	23.25	0.12
54	515000	3570000	Q	18	7.90	590	383	23.6	0.00	187.65	109.2	6.02	56.0	16.81	41.20	0.54	5.98	5.90	0.72
55	485000	3590000	Q	19	7.93	605	401	17.3	0.00	179.79	137.8	6.31	57.4	18.60	42.24	0.94	6.25	6.05	1.02

APPENDIX 1

Table 2 Surface water chemistry data of 6 stations along the Zayandeh Rud (average over the period 1991-1998)

Pole Chom Station

	TDS	EC	PH	CO3	HCO3	Cl	SO4	SUMAN	Ca	Mg	Na	K	SUMC	EC/100	error	SAR	%Na
	mg/l			meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l				
avg	500	762	7.5	0	3.549	1.952	2.284	7.785	3.617	1.651	2.490	0.069	7.828	7.62	0.69	1.51	30
max	931	1433	8.7	0	7.000	4.700	6.280	14.200	5.500	4.200	6.000	0.400	14.730	14.33	5.65	3.37	47
min	270	415	7.0	0	1.100	0.500	0.300	4.100	1.100	0.700	1.000	0.000	4.080	4.15	0.00	0.71	3
stdev	170	250	0.3	0	0.779	1.035	1.251	2.544	0.900	0.729	1.229	0.078	2.542	2.50	0.97	0.57	7

Pole Zamankhan Station

	TDS	EC	PH	CO3	HCO3	Cl	SO4	SUMAN	Ca	Mg	Na	K	SUMC	EC/100	error	SAR	%Na
	mg/l			meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l				
avg	215	329	7.7	0	2.595	0.365	0.416	3.376	2.274	0.696	0.387	0.040	3.398	3.29	1.09	0.32	12
max	295	450	8.2	0	3.100	1.100	1.100	4.400	2.900	1.600	1.100	0.440	4.400	4.50	6.87	0.91	81
min	145	220	5.5	0	1.800	0.200	0.100	2.300	1.400	0.200	0.100	0.000	2.380	2.20	0.00	0.10	4
stdev	26	37	0.4	0	0.263	0.110	0.239	0.358	0.289	0.296	0.171	0.082	0.369	0.37	1.39	0.14	9

Musiyan

	TDS	EC	PH	CO3	HCO3	Cl	SO4	SUMAN	Ca	Mg	Na	K	SUMC	EC/100	error	SAR	%Na
	mg/l			meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l				
avg	382	584	7.7	0	3.018	1.386	1.838	6.243	3.091	1.300	1.811	0.020	6.222	5.84	0.28	1.19	28
max	745	1065	8.2	0	3.600	3.600	3.930	10.830	4.800	2.100	4.350	0.100	10.880	10.65	1.05	2.41	40
min	269	414	7.4	0	2.400	0.500	0.740	4.440	2.300	0.800	0.900	0.000	4.400	4.14	0.00	0.70	21
stdev	133	195	0.2	0	0.277	0.919	0.886	1.958	0.726	0.359	1.016	0.024	1.966	1.95	0.28	0.51	6

Pole Kaleh Station

	TDS	EC	PH	CO3	HCO3	Cl	SO4	SUMAN	Ca	Mg	Na	K	SUMC	EC/100	error	SAR	%Na
	mg/l			meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l				
avg	239	366	7.7	0	2.682	0.413	0.758	3.852	2.379	0.838	0.601	0.015	3.833	3.66	0.94	1.42	15
max	342	527	8.2	0	3.200	1.000	2.630	5.800	3.500	2.200	1.680	0.040	5.860	5.27	19.64	51.00	32
min	157	242	7.3	0	1.500	0.200	0.120	2.520	1.200	0.400	0.200	0.000	2.560	2.42	0.00	0.19	0
stdev	46	71	0.2	0	0.341	0.156	0.573	0.790	0.494	0.354	0.382	0.011	0.783	0.71	2.60	6.76	7

APPENDIX 1

Table 2 (continued)

Lenj Station Nekouabad

	TDS mg/l	EC	PH	CO3 meq/l	HCO3 meq/l	Cl meq/l	SO4 meq/l	SUMAN meq/l	Ca meq/l	Mg meq/l	Na meq/l	K meq/l	SUMC meq/l	EC/100	error	SAR	%Na
avg	375	575	7.7	0	2.845	1.359	1.787	5.990	3.000	1.307	1.650	0.029	5.986	5.75	0.45	1.10	26
max	709	1014	8.0	0	3.700	3.800	4.000	10.400	5.000	2.800	4.350	0.300	10.390	10.14	2.48	2.51	42
min	258	397	7.1	0	1.700	0.400	0.540	4.220	1.400	0.500	0.400	0.000	4.270	3.97	0.00	0.25	7
stdev	124	185	0.2	0	0.358	0.936	0.893	1.797	0.811	0.550	0.946	0.056	1.801	1.85	0.49	0.51	7

Varzaneh Station

	TDS mg/l	EC	PH	CO3 meq/l	HCO3 meq/l	Cl meq/l	SO4 meq/l	SUMAN meq/l	Ca meq/l	Mg meq/l	Na meq/l	K meq/l	SUMC meq/l	EC/100	error	SAR	%Na
avg	13502	17696	7.5	0	4.429	184.507	17.800	206.700	13.482	31.769	159.262	0.895	205.408	176.96	0.66	32.70	75
max	31514	45091	8.3	0	10.100	532.000	172.100	662.500	43.200	86.800	556.000	2.900	664.550	450.91	8.98	84.38	93
min	1065	1136	6.9	0	2.600	7.000	2.550	15.900	2.800	2.100	10.000	0.050	15.950	11.36	0.00	5.68	61
stdev	8046	11313	0.3	0	1.043	127.081	28.344	139.622	7.191	19.862	115.361	0.677	138.441	113.13	1.77	18.21	6

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