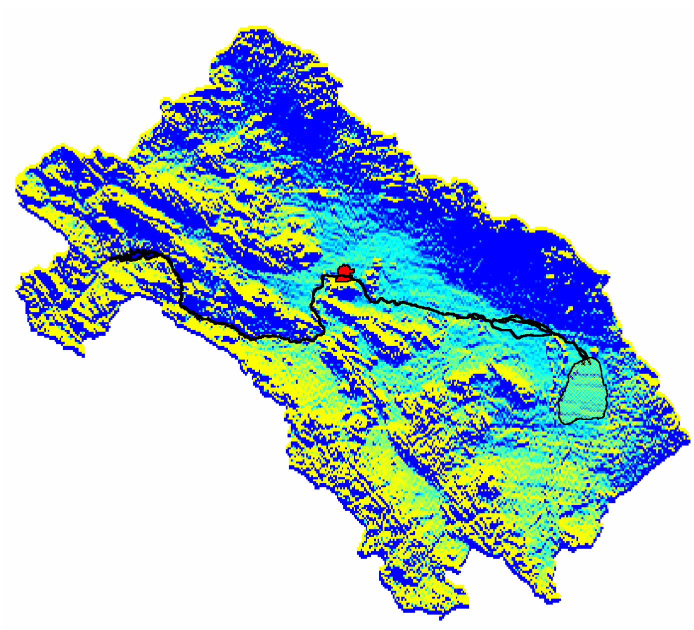
Sustainable Irrigation and Water Management in the Zayandeh Rud Basin, Iran

Groundwater Resources Modeling of the Lenjenat Aquifer System

A. Gieske, M. Miranzadeh



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Abstract

Irrigated agriculture does not only depend on surface water but also on groundwater. Within the main irrigation districts, the groundwater table is usually close to the surface and here the groundwater is used to supplement or replace the surface water in times of drought. However, as one moves away from the Zayandeh towards the hills and mountain ranges bordering the basin, people tend to rely much more heavily on groundwater from qanats, springs and tube wells.

This paper studies the groundwater movement in the Lenjanat District, one of the smaller districts in the Basin. After an analysis of the available data on ground water levels and abstractions, a conceptual model is built of the Lenjanat Southern Plains Aquifer, which is then translated into a steady state computer model. This model provides a clear insight in the relation between the main water balance components under steady state conditions: average recharge, abstraction, inflow and outflow.

Although the data do not permit the construction of a full transient model at present, some longer-term time series data is presented with regard to trends in ground water levels, qanat and spring flow in the last ten years.

1 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. Murray-Rust et al. (2000) described the basin's hydrology.

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 (Murray-Rust and Salemi, 2002).

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

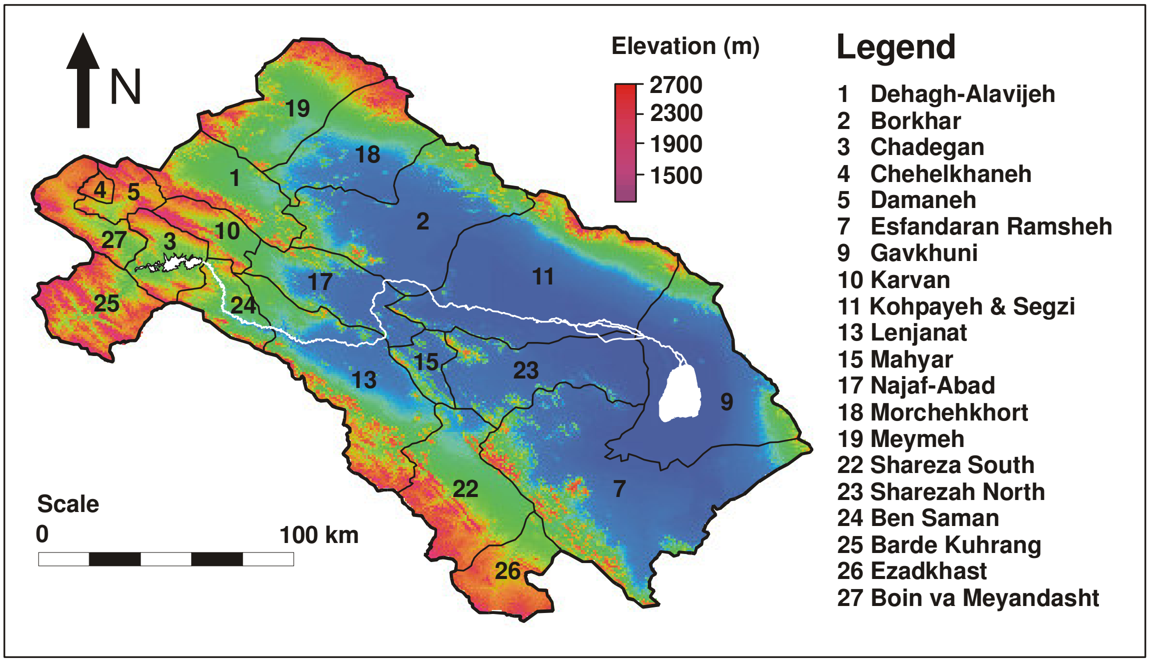

Fig. 1a Hydrological Districts in the Zayandeh Rud Basin. The elevations shown here on a 1x1 km grid, are derived from the digital chart of the world.

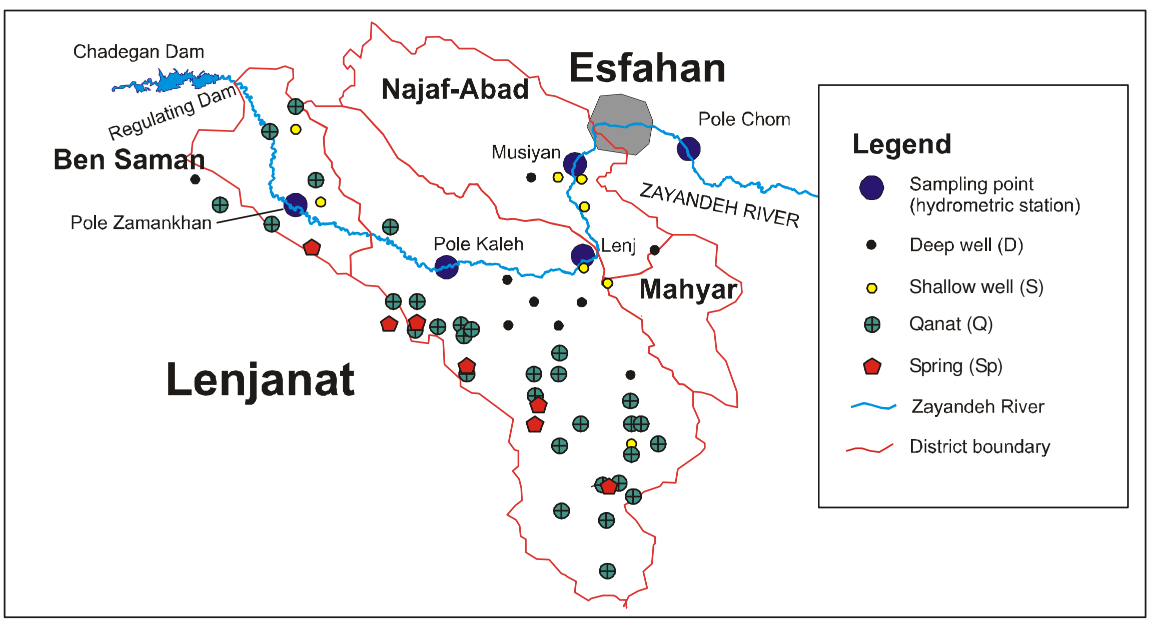

Fig. 1b Location map, showing wells, qanats and springs in the Lenjanat, Ben Saman and Najaf-Abad hydrological subcatchments, plotted on a 5x5 km grid. Also shown are the surface water sampling points.

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.

There is a highly complementary relationship between the use of surface water and groundwater. In times of drought surface water is less easily available and as a result the abstraction of groundwater is intensified leading to decline in groundwater levels (Droogers and Miranzadeh, 2001) and loss of groundwater quality. When dams fill up after good rains or snowfall, surface water is used predominantly again and groundwater levels may slowly recover as a result of natural recharge by precipitation, by infiltration from the Zayandeh Rud or by excess irrigation water leaching to the groundwater table.

In this paper a study is made of the groundwater flow patterns in the Lenjanat District which lies upstream of the major irrigation districts. It was suggested by Gieske et al. (2000) that the solute content of the groundwater seeping into the Zayandeh Rud constitutes one of the factors responsible for the increasing salinity of the Zayandeh River water on its way towards the east. Whereas it is reasonably clear that seepage of groundwater into the river made an important contribution to the river's flow in the past, it is not so clear what the situation is at present.

Therefore a numerical modelling study of the Lenjanat groundwater system was made with the package PMWIN (Chiang and Kinzelbach, 1998). The study area and data sets are discussed in respectively sections 2 and 3, while the aquifer's conceptual model is outlined in section 4. The steady state model results are given in section 5, while some transient aspects are illustrated section 6 with a few hydrographs of representative wells, qanats and springs. Finally a discussion of the aquifer water balance aspects is given in section 7 with some conclusions in regard to recharge, transmissivity and seepage into the Zayandeh.

2 Study area

The Lenjanat subcatchment (including the Ben Saman District to the west) is surrounded by NE-SW trending mountain ranges (see Fig. 1a) rising 800 to 1000 m above the plains. In the southern part these are the Zard Kuhbakhtiari Mountains. In the west the Ben Saman district is 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 Lenjanat administrative hydrogeological district is about 3200 km^2 in size, and covers both the Ben Saman and old Lenjanat District.

Wedged between these mountain ranges and the Zayandeh Rud is a large plain with an area of about 1250 km^2 descending from the foot of the mountain slopes (1900 m) towards the river (1650 m). Below this plain a high yielding aquifer has formed from which water is taken by qanats, springs, deep and shallow wells. Rainfall is erratic and

Table 1 Lenjanat District Summary Hydrogeological Data (Ministry of Power, 1997-1998)

	number	minimum	maximum	average	total
Elevation				1600m	
Total area					3433km^2
Area plains only					1707km^2
Rainfall				220mm	
Depth water level				20m	
Deep wells					
number	538				
size		74m	150m		
discharge			52 ltr/s	11 ltr/s	95 MCM/yr
Shallow wells					
number	738				
size		16m	49m		
discharge					49 MCM/yr
Qanats					
number	369				
discharge			285 ltr/s	13 ltr/s	156 MCM/yr
Springs					
number	169				
discharge			370 ltr/s	8 ltr/s	41 MCM/yr
Total Abstraction					341 MCM/yr
Piezometers					
number	43				
total length					1706m
Exploration wells					
number	4				
total length					392m
Soundings (VES)	134				
Observation wells	43				
Representative wells	7				
Representative qanats	26				
Representative springs	5				
Water use	MCM/yr				
Domestic	20				
Industrial	2				
Agricultural	319				

on average 220 mm per year. Vertical diffuse recharge through the valley floor is low and probably in the order of 3 % or about 7 mm/yr (Gieske, 1992).

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. Fig. 1b shows the sampled wells, qanats and springs in the area.

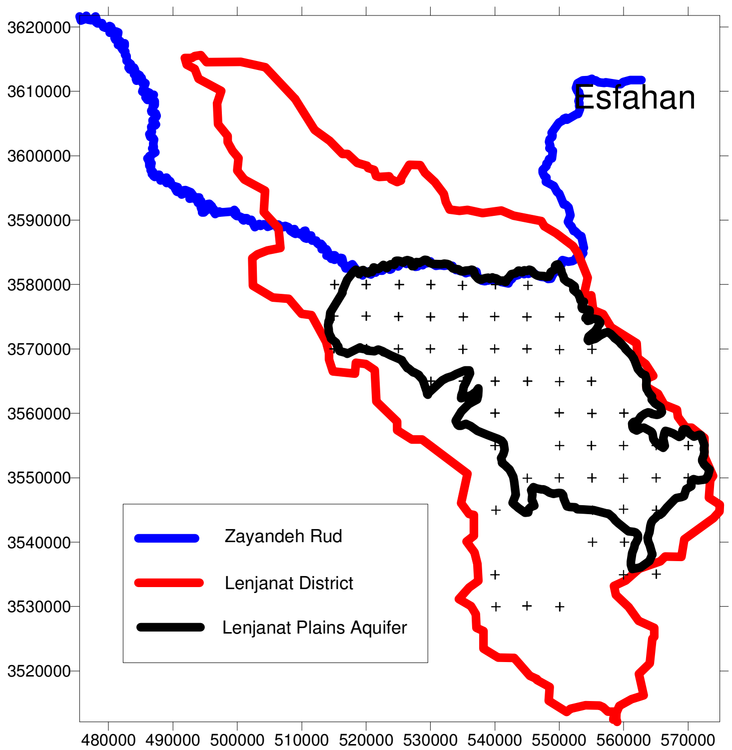

Fig. 2 The figure shows the Lenjanat District (red line) with the Zayandeh Rud flowing from West to East (blue line). The black line indicates the boundary of the Lenjanat Plains Aquifer (see section 4), while the symbols show the position of the abstraction wells on the lower left corner of the grid cells they are in.

3 Data sets

The amount and type of data that is collected by the Ministry of Power is illustrated in Table1, where the available hydrogeological data for Lenjanat District have been summarized. For the present modelling study of the groundwater resources of the Lenjanat groundwater system the following categories are important:

Piezometer data (groundwater level fluctuations)

The groundwater level database was kindly made available by Mr A.A. Saberi (Ministry of Power, Esfahan Office). This database consists of more than 60000 well level

observations for over 700 observation wells in the entire Zauandeh Rud Basin, covering the period from 1987 to 2000. Droogers and Miranzadeh (2001) already used this database in their analysis of long-term trends in groundwater levels. Here a subset is selected according to the boundaries of the Lenjanat District and in particular to those of the Plains Aquifer. A distinction is made between shallow and deep wells. Fig. 3 shows the distribution of these wells over the Lenjanat district. The groundwater levels of 1997 (1376) were used for the steady state modelling.

Abstraction from wells

Although the information as summarized in Table 1 is available for 1998, more detailed information with respect to discharges and grid positions for individual boreholes was only found for 1988. Complete borehole inventories are only made occasionally. It was decided therefore to use the 1988 data for the indicative modelling intended here. Figure 2 shows the positions of the wells used. It should be noted that many wells inside grid cells are condensed into a single point in the lower left corner of the grid cells. Some wells are positioned in the mountain range to the south of the plains aquifer. Although they are clearly in the Lenjanat district they are not in the aquifer, and are therefore left out of the aquifer water balance calculations.

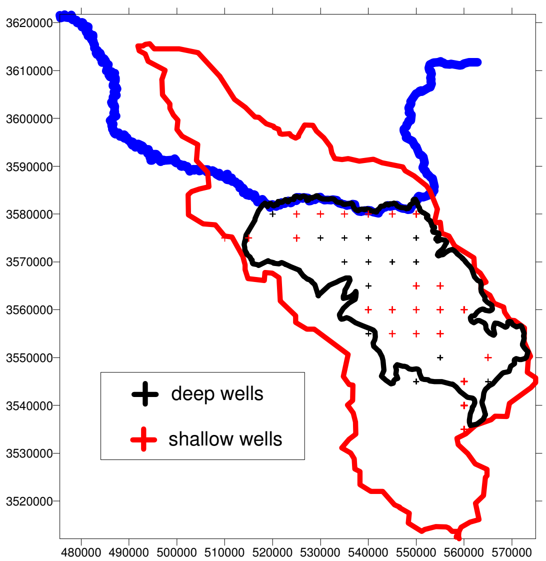

Fig. 3 The figure shows the position of the deep and shallow observation wells in the aquifer. Note that shallow wells are also present in the central part of the aquifer. This is related to the aquifer transmissivities (see section 5).

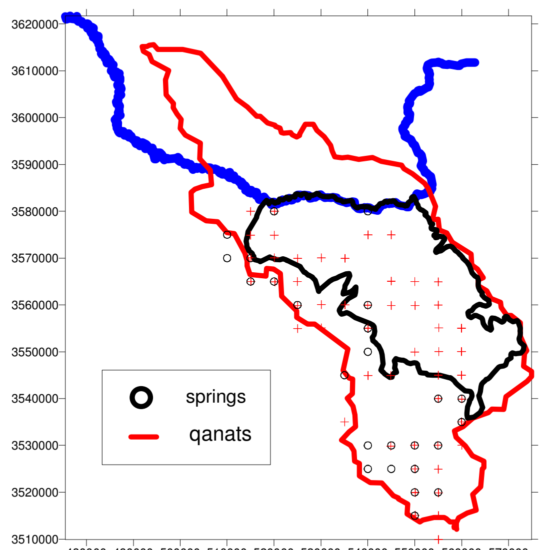

Fig. 4 The figure shows the positions of the qanats (red crosses) and the springs (black circles). Qanats are found in both the mountains and plains, whereas the springs mostly occur in the mountains. A few springs are found along the Zayandeh Rud

Abstraction from qanats and springs

Fig. 4 shows the distribution of qanats and springs in the southern part of the Lenjanat District. The figure indicates clearly that the majority of springs lie in the mountainous area. As a matter of fact many springs lie on the boundary between mountains and plains as could be expected. Some springs lie close to the Zayandeh Rud indicating that groundwater does flow towards the river, or has flown towards the river in the recent past. The qanats are more evenly distributed over plains and mountains. The qanats and springs in the mountains have also been left out of the aquifer's water balance calculations. It is assumed that this outflow is used up to a large extent. Most of the inflow from the mountainous area into the plains appears to occur through subsurface flow. In the steady state modelling assumptions are made with regard to the magnitude of this lateral inflow, which makes up the larger part of the recharge to the plains aquifer.

The abstraction information is summarized in Table 2 below. The 1988 well abstraction in the Plains Aquifer is higher than the statistics for 1998 (the entire Lenjanat District). The other values correspond better to what one would expect. There are fewer springs and qanats in the actual aquifer area than in the mountains. In the following it is assumed that about 10 to 20 % of the abstracted water is returned to the groundwater system. The steady state model uses 200 MCM/yr abstractions as an initial value.

Table 2 Abstraction data of the Lenjanat Plains Aquifer (all figures in MCM/yr)

	Ministry of Power Lenjanat and Ben Saman 1997-1998 data	Lenjanat District 1988 data	Lenjanat Plains Aquifer 1988 data
Wells (deep and shallow)	150	187	158
Qanats	156	135	75
Springs	41	32	7

Groundwater recharge by rain

As mentioned before, the average rainfall in the area is about 220 mm per year and in this arid to semi-arid climatic regime, diffuse recharge is thought to be in the order of 6 mm/yr (Gieske, 1992). It is shown in the following sections that the precise value of this recharge is not important because it is negligible compared to the lateral recharge of the basin.

Hydrogeological information

Aquifer transmissivity and storativity values can be derived from pumping tests. A few documented tests are available in the area and the locations are shown in Figure 5 below. Jenatabad lies close to the Zayandeh, Ghaleh Hakim is a further away from the river, while Haft Yki lies at the foot of the mountains. The pumping test data were analyzed with the AQUITEST software package (Roehrich, 1996) and results are summarized in Table3. It is assumed here that the two tests per location refer to different positions in the 5x5 km grid cells. The results show an enormous variation in transmissivity and storativity values. The high values appear to originate from alluvial fan structures and braided subsurface riverbeds of coarse gravels and pebbles, while the lower T values are commonly found in clayey-sandy flood plain deposits. The few available lithological logs mainly indicate sand-clay materials. The variation in storage coefficients points at varying confined-unconfined conditions, such as is frequently the case when an alternating and laterally heterogeneous sequence of fine and coarse deposits is found.

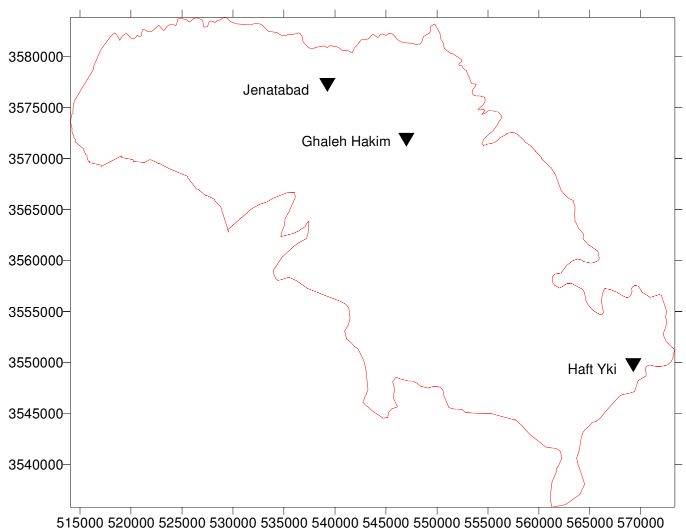

Fig. 5 The three pumping well positions are shown in the aquifer.
(see Table 3)

Table 3 Pumping test results for the aquifer transmissivity and storage (date approx. 1992). The well locations are indicated in Fig. 5.

		Jacob method		Theis method		Recovery method		Hantush method	
		T	S	T	S	T	k	T	S
		m^2day^{-1}		m^2day^{-1}		m^2day^{-1}	$mday^{-1}$	m^2day^{-1}	
Jenatabad	test1	8240	9.30E-04	11000	8.85E-05	5590	111	-	-
	test2	76.3	3.40E-04	78.5	3.14E-04	-	-	-	-
Ghaleh Hakim	test1	1730	0.2	1860	0.21	1100	22	-	-
	test2	7.3	1.00E-07	8.3	4.00E-08	3.34	0.067	2.94	3.00E-06
Haft Yki	test1	786	6.80E-03	687	8.67E-08	691	13.80	-	-
	test2	41.5	4.00E-07	51.6	8.00E-08	-	-	3.25	2.60E-05

Finally, to cope with the amount of data several simplifications are usually made in the administrative procedures for recording and analysis of the data.

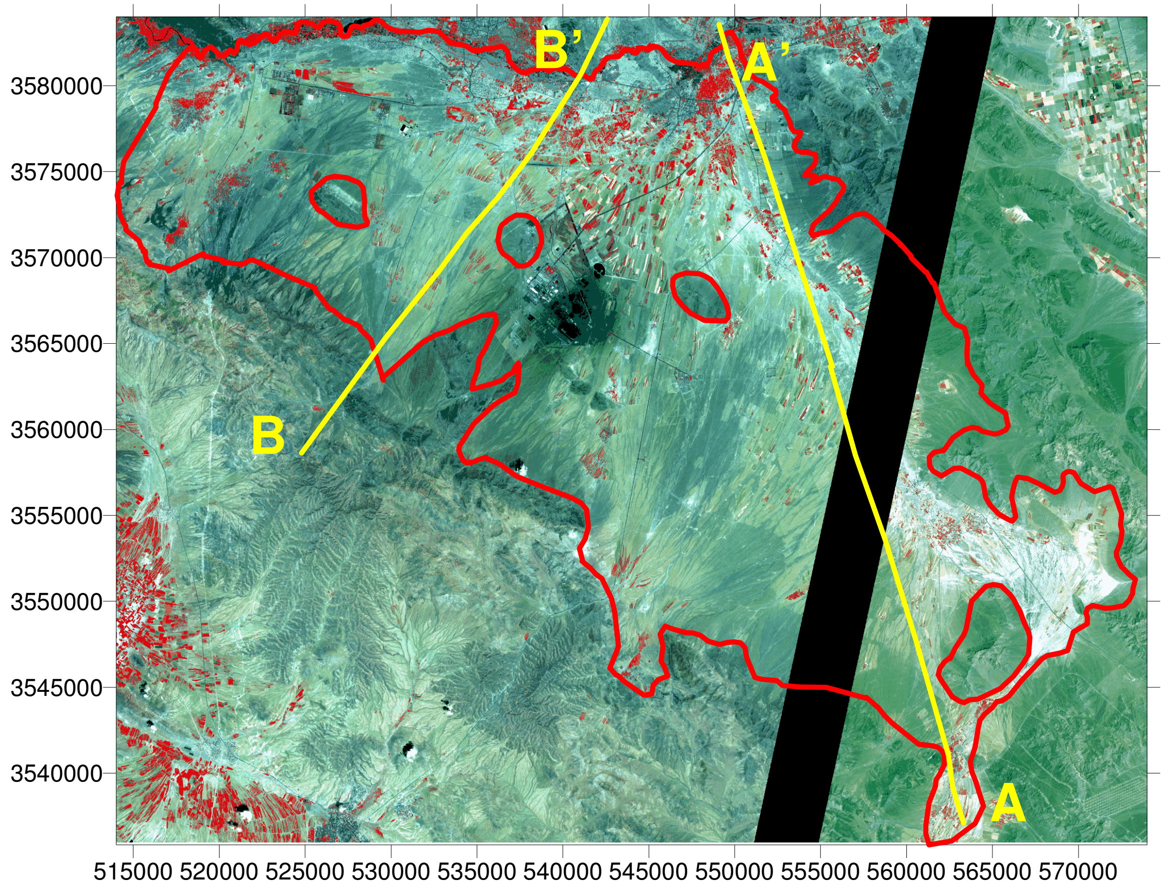

Fig. 6 The aquifer boundaries were delineated on a combination of two Aster images (2001). These images have a resolution of 15 m, so they provide better detail than Landsat images which have a pixel size of 30 m. The two images are not overlapping, hence the gap. The image is a False Colour Composite of bands 3, 2 and 1, hence the green vegetation shows up in red colours. The black spot in the centre is the location of Mubarake Steel Factory

Grid cells

In general wells, qanats and springs are combined in 5x5 km UTM grid cells. That is, all wells, qanats and springs are given the UTM coordinates of the lower left corner of the grid cell they are in. This leads to many duplicate positions and problems in the spatial analysis. Sometimes maps are available with well, qanat and spring positions plotted more precisely, but this is not usually the case.

Representative Wells

Because of the huge amount of qanats, springs and wells it is not practically possible to monitor all levels and discharges on a regular basis. Therefore only a selected number of wells – the so-called representative wells - have been selected per district for regular monitoring routines. A complete well inventory is made only at intervals of several years.

4 *Conceptual model*

First the lateral boundaries of the aquifer were determined with two ASTER (2001) images, mosaicked on the same coordinate system. The boundaries were drawn along the Zayandeh Rud in the North (constant head boundary) and at the foot of the mountain ranges. Moreover, a few hills in the plains are assumed to be impermeable to groundwater flow and are marked with a red line in figure 6 below.

The yellow lines in Fig. 6 mark two cross-sections AA' and BB' showing both surface and groundwater levels. The surface elevations are derived from the Digital Elevation Map (GTOPO30, see Fig.1) while the groundwater levels along the transect are determined from a kriged map of the groundwater levels (1997 data). The cross-sections indicate that the groundwater levels generally follow the topography. Although it appears that the groundwater is rather deep near A, it should be noted that the DEM only has a resolution of 1km and is therefore not accurate in mountainous terrain with steeply incised valleys. Figures 7 and 8 also show that near the river the groundwater level reaches the Zayandeh Rud's water level. The conclusion is therefore that when abstractions are not too high, groundwater does seep into the river.

Furthermore, Fig. 7 shows that the groundwater levels are close to the surface about half-way between A and A' as was already indicated by the presence of shallow wells (see Fig.3). From a hydrogeological point of view there are various possible explanations, surface slope changes and low aquifer transmissivities just down slope of the shallow well region. This aspect will be addressed further in the next section.

Figure 8 indicates clearly that the aquifer boundaries have to be drawn at the foot slopes of the southern mountain range and at the Zayandeh Rud. The river has been taken as a constant head boundary, while the mountains form a no-flow boundary. The active model cells just north of the mountain are receiving a constant flow, representative of the annual average mountain front recharge.

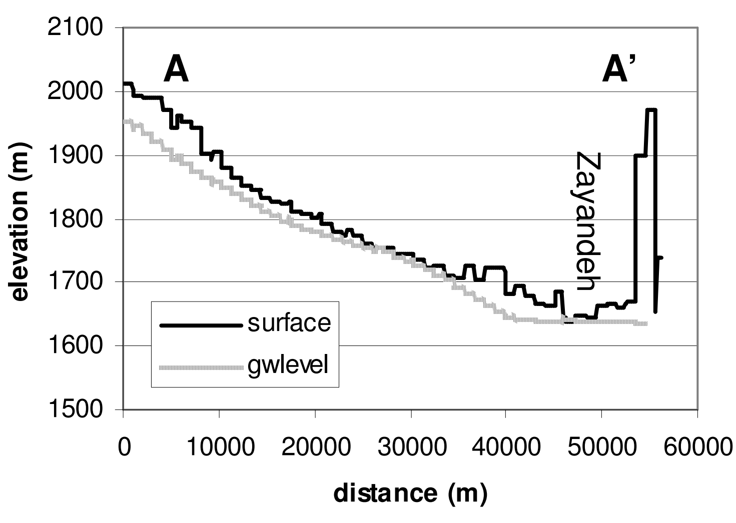

Fig. 7 Cross-section AA' of the aquifer from the South to North. The location of the cross-section has been indicated in Fig.6. The surface elevation has been determined with the DEM (see Fig. 1), while the groundwater elevation has been found through kriging the groundwater levels of the observation wells.

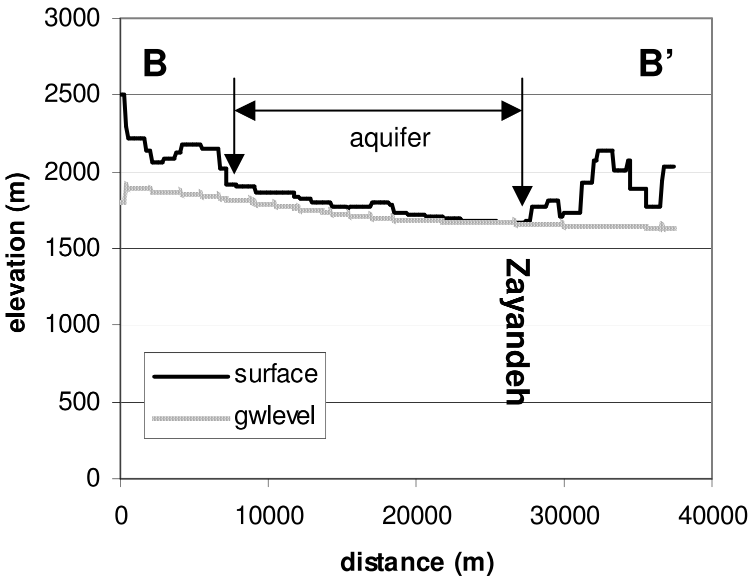

Fig. 8 Cross-section BB' of the aquifer from North to South (see also Fig. 6). the Zard Kuhbakhtiari mountains form the aquifer boundary in the South, while the Zayandeh Rud forms the northern boundary.

The eastern aquifer boundary is the mountain range extending towards the Zayandeh Rud in northwesterly direction. The western aquifer limit is taken as the boundary between the Lenjanat and Ben Saman Districts (Fig. 1) which appears to be parallel to the flow direction and which therefore may be taken as a no-flow boundary in the model.

Finally, the question with regard to the thickness of the saturated zone and the depth to the aquifer's bottom is more difficult to answer. The aquifer's thickness is probably highly variable in view of the small rocky hills that are visible on the surface. One should visualize the aquifer as a weathered sedimentary rock of low permeability with an irregular surface, overlain by successions of coarse erosional deposits and fine sand-clay layers.

The satellite image (Fig. 6) shows large alluvial fans emanating from the Zard Kubakhtiari mountains in northeasterly direction. The flow lines visible on these fans are clearly indicative of the subsurface groundwater flow. The combination of coarse

sedimentary material with a succession of sand-clay lenses leads to partly confined-partly unconfined behaviour of the groundwater. As a first approximation in the exploratory aquifer modelling, the aquifer is taken as confined of constant thickness, while its hydraulic conductivity is taken as variable.

5 *PMWIN model results*

The groundwater modelling package PMWIN (Chiang and Kinzelbach, 1998) started as a pre-and postprocessor for the MODFLOW finite difference groundwater flow model by McDonald and Harbaugh (1988). However, PMWIN now incorporates many other applications as well, such as for example the advective transport model PMPATH, the solute transport model MT3D, the non-linear optimization models PEST and UCODE. Here we use PMWIN to run MODFLOW steady state simulations of the aquifer.

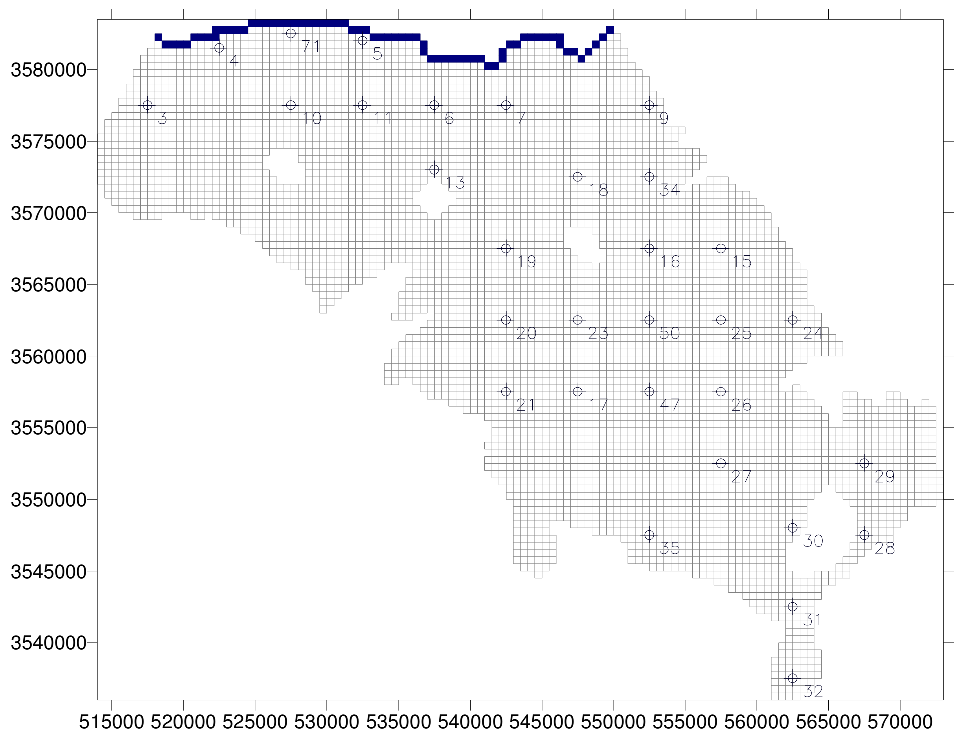

Fig. 9 The figure shows the aquifer discretized in 500x500m grid cells. The total number of cells in the model amounts to 4996, with a total area of 1249 km^2.

Model Assembly

As was discussed in the previous section the aquifer boundaries were delineated with two geocorrected Aster images (2001). The Zayandeh Rud river is taken as a constant head boundary, whereas all other boundaries are no-flow boundaries. The aquifer is modelled as a single layer confined system with a thickness of 50 m. In this approximation the groundwater level is considered to be a piezometric head. Although in reality the aquifer probably has more unconfined than confined characteristics, the approximation is rather good in any case. The rectangle in Fig. 9 is subdivided in 103 rows and 125 columns. The actual model area comprises 4996 active cells with a total area of 1249 km^2. From the database of available piezometer records the well levels of May 1997 were selected and these levels were then averaged for the grid cells. The coordinates were transformed from the lower left corner of the grid cells to the centre by adding 2500 m to both x- and y-coordinates.

The following maps were prepared for MODFLOW input (all as 103x125 ASCII matrices):

Grid

This map is shown in Fig.9 and contains the grid and cell dimensions, together with the conditions (-1 for constant head, 0 for inactive and 1 for active cells).

Initial hydraulic head

This map is based on the observed water levels of May 1997. It will be changed during the calculations in accordance with the modelled flow through the aquifer. After the calculations the heads are retrieved at the positions of the observation wells, so that they can be compared with the observed ones.

Horizontal hydraulic conductivity K

The horizontal conductivity is set at 50 md^{-1} initially. This corresponds to a transmissivity T of 2500 m^2d^{-1}. During the calibration stage this map is slowly changed because of the need to arrive at calculated heads that are as close as possible to the observed ones. It is necessary to introduce different K values for different regions of the aquifer.

Recharge

Two different types of recharge were entered in the recharge map. First a recharge by rain component was entered in each cell. As mentioned before the recharge is estimated at 6 mm on average annually. This leads to a small contribution of only 7.5 $MCMyr^{-1}$ over the aquifer. Secondly, a much more important contribution lies in mountain front recharge, and subsurface inflow from the mountains. A large number of recharge grid cells were placed close to the mountains, each with a recharge of 1.2 $MCMyr^{-1}$. During the

modelling process the number of cells with this recharge was changed depending on the computed heads. Initially a total recharge of about 300 $MCMyr^{-1}$ was assumed.

Abstraction by wells, qanats and springs

All contributions were added together and averaged over 5x5 km grid cells. Table 4 shows that over the aquifer area the total abstraction amounted to 240 $MCMyr^{-1}$ in 1988. This figure may have to be modified somewhat in view of the return flow of 10 –20%, and in view of the fact that the abstraction in 1997 was probably higher than in 1988. However, this map was also updated regularly as a result of the head calculations.

In summary, at each step the calculated heads are compared with the observed ones, and one tries to minimize the differences systematically by changing the maps of the conductivity K, the recharge distribution and the abstraction. This process is initially carried out manually by studying the effect of parameter changes. At a later stage non-linear optimization packages PEST or UCODE may be used to minimize the differences between observed and calculated heads.

Calibration

The optimisation criterion is defined as minimization of the root mean square error (RMSE), defined by

$$RMSE = \sqrt{\frac{\sum \left(h_{obs,i} - h_{calc,i}\right)^2}{n}}$$

where $h_{calc,i}$ are the calculated heads, $h_{obs,i}$ the observed heads and n the number of observations. After going through step by step variation of the input parameters, a RMSE of 22.6 m was obtained. Fig. 10 below shows the comparison between observed and calculated heads in a scatter diagram. Normally, the RMSE is much smaller. However, in the present situation the positions are known only with a precision of ± 2.5 km while the hydraulic gradients are in the order of 50m over 5km. The grid cell convention is thus a severely limiting factor in this case. All observed and calculated heads are compiled in Appendix 1.

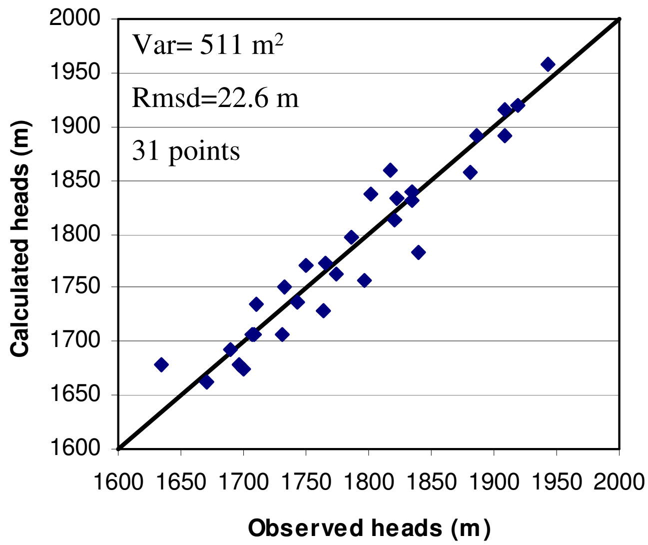

Fig. 10 Scatter diagram of the calculated against the observed heads.

The outcome of the modelling process is a steady state volumetric budget, which is given below as Table 4. The total seepage into the river is 76 $MCMyr^{-1}$, the total abstraction from the wells, qanats and springs amounts to 192 $MCMyr^{-1}$, while the total recharge is about 267 $MCMyr^{-1}$. The model shows that under these conditions the groundwater flow components are in balance. If the total outflow is larger than 267 $MCMyr^{-1}$ then groundwater levels will drop. This point will be further discussed in the next section.

Table 4 Volumetric budget for the steady state model

	m^3d^{-1}	$MCMyr^{-1}$
seepage into the river	207003	76
wells, qanats, springs	524754	192
	total	267
lateral and diffuse recharge	731757	267

Further results

The calculated groundwater level contour map is shown below in Fig. 11. The groundwater will flow perpendicular to the contour lines, mostly in northeasterly direction. The flow from the bottom right corner of the figure is expected to flow straight north. However, the exception to this is the outflow from the large alluvial fan (see Fig. 6). The flow here appears to the east, which probably may be explained by a zone of low transmissivity on the north side of the fan.

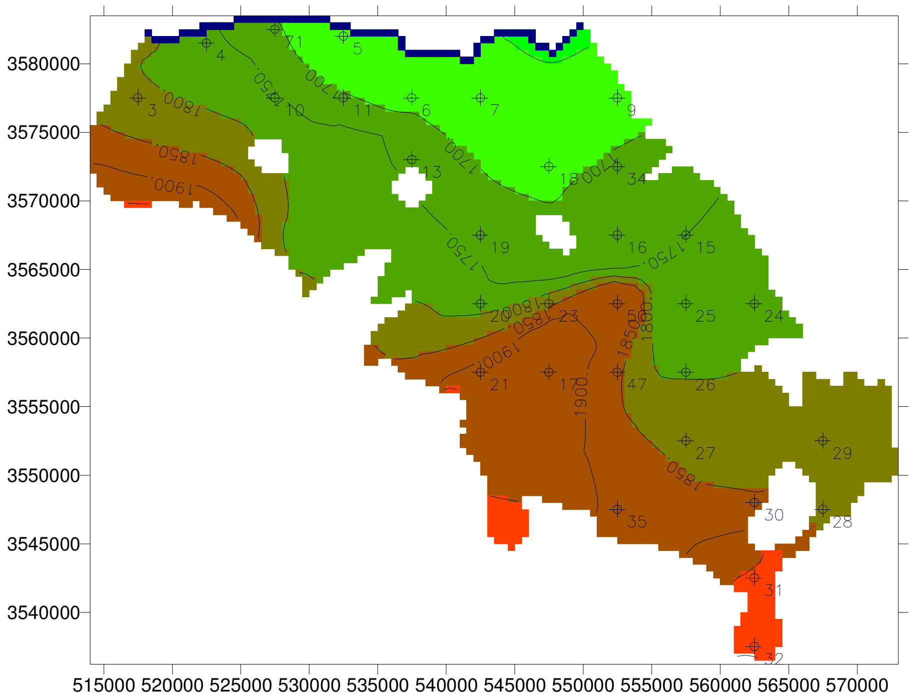

Fig. 11 Groundwater level contour map from the PMWIN and MODFLOW model calculations

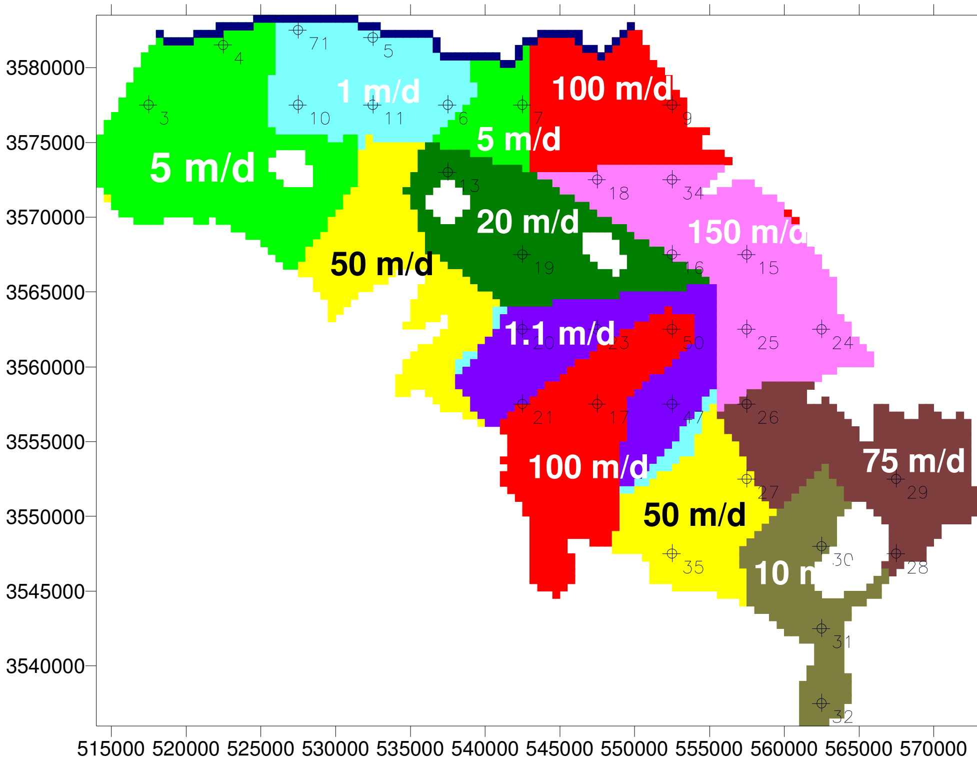

Fig. 12 Modelled hydraulic conductivities lie between 1 and 150 md^{-1}, corresponding to a transmissivity range from 50 to 7500 m^{2}d^{-1}.

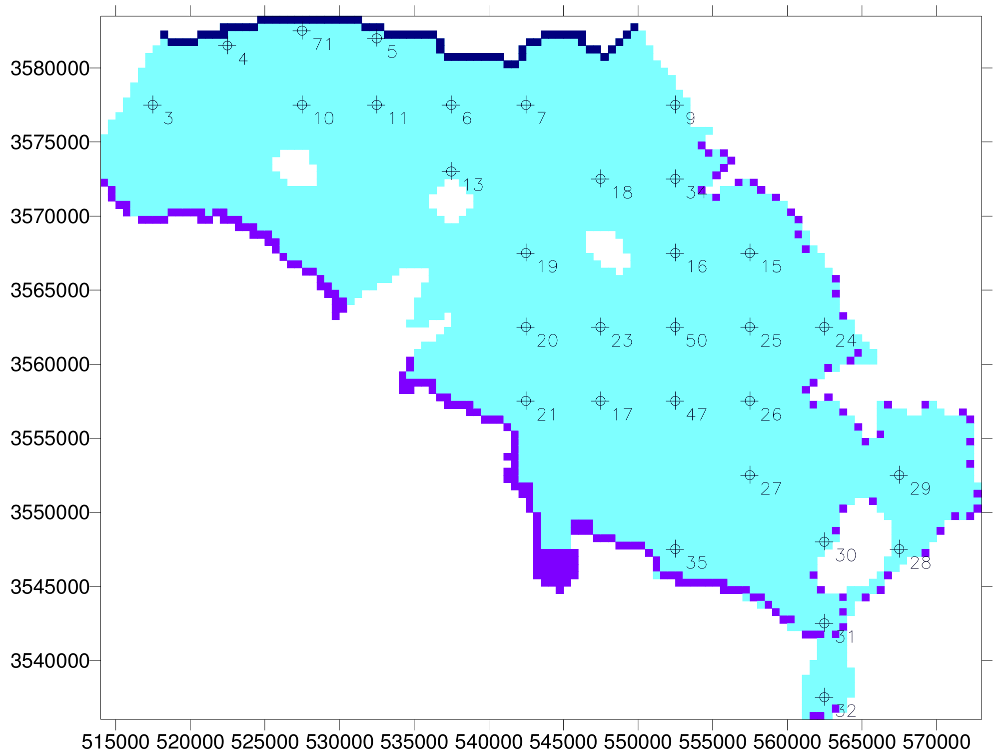

Fig. 13 Recharge rates are 6mmyr^{-1} for the light blue area, whereas recharge for the purple cells is in the order of 13.2 mmd^{-1}.

Fig. 12 shows the zones of hydraulic conductivity that were introduced in the model during the calibration process. Low conductivity zones occur mainly near the river. An exception to this is the low permeability barrier around the alluvial fan. The hydraulic conductivities of Fig. 12 can be multiplied by the aquifer thickness (50m) to obtain transmissivity values from 5 to 7500 m^{2}d^{-1}. The range of these values agrees rather well with the results of the pumping tests (Table 3).

Finally, Fig. 13 shows the recharge pattern, where the lightblue color indicates a direct recharge of 6 mmyr^{-1}, which is negligible compared to the lateral recharge along the mountain ranges. One purple grid cell of 500x500 m corresponds to a recharge value of 12.3 mmd^{-1} or 1.2 MCM/yr.

6 Temporal Aspects

Discharge from qanats and springs

The records of the representative qanat and spring discharges are available from 1367-1379 (1988-2000). Below two examples are given of the change of discharge with time for a qanat and a spring (Figs 14 and 15). The negative trend is clearly visible. Discharges of both the qanat and the spring have been reduced by 50% since 1988. Table 5 below

gives a summary of the statistics of the three representative springs and 9 representative qanats in the Lenajat Plains Aquifer area. On average the discharge from qanats and springs is reduced by about 2% annually over the period 1988-2000. One spring and one qanat have a positive trend, their discharge is slightly increasing over the time period considered.

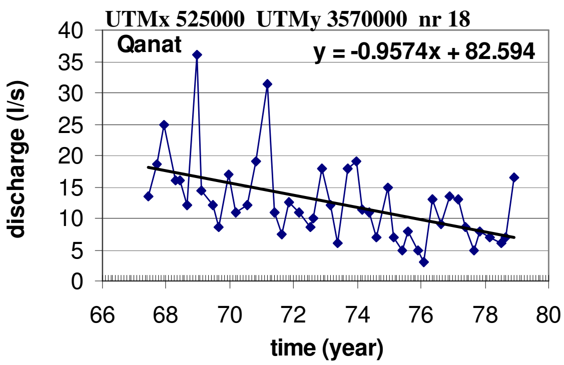

Fig. 14 Discharge of qanat in northwestern part the Lenjanat Aquifer from 1367-1379 (1988-2000)

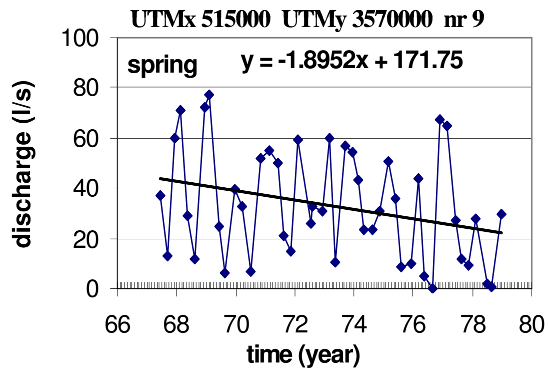

Fig. 15 Spring discharge in north-of western Lenjanat from 1367-1379. (1988-2000)

Table 5 Trend analysis of the representative springs and qanats in the aquifer

	number	x (m)	y (m)	regresssion coeffs slope	offset	discharge 1368 1989 (l/s)	discharge 1378 1999 (l/s)	annual difference %
spring	8	542500	3552500	0.3301	33.364	55.81	59.11	0.59
	9	517500	3572500	-1.8952	171.750	42.88	23.92	-4.42
	23	557500	3542500	-0.0561	10.867	7.05	6.49	-0.80
							average	**-1.54** %
qanat	3	547500	3547500	-0.6791	95.109	48.93	42.14	-1.39
	4	527500	3572500	-0.7069	61.054	12.98	5.92	-5.44
	6	547500	3562500	-0.0055	32.682	32.31	32.25	-0.02
	16	562500	3557500	-0.0667	16.283	11.75	11.08	-0.57
	17	517500	3577500	-0.9129	78.731	16.65	7.52	-5.48
	18	527500	3572500	-0.9677	83.367	17.56	7.89	-5.51
	19	562500	3547500	-0.1390	20.858	11.41	10.02	-1.22
	21	542500	3557500	0.1273	38.847	47.50	48.78	0.27
	24	547500	3577500	-0.0895	17.642	11.56	10.66	-0.77
							average	**-2.24** %

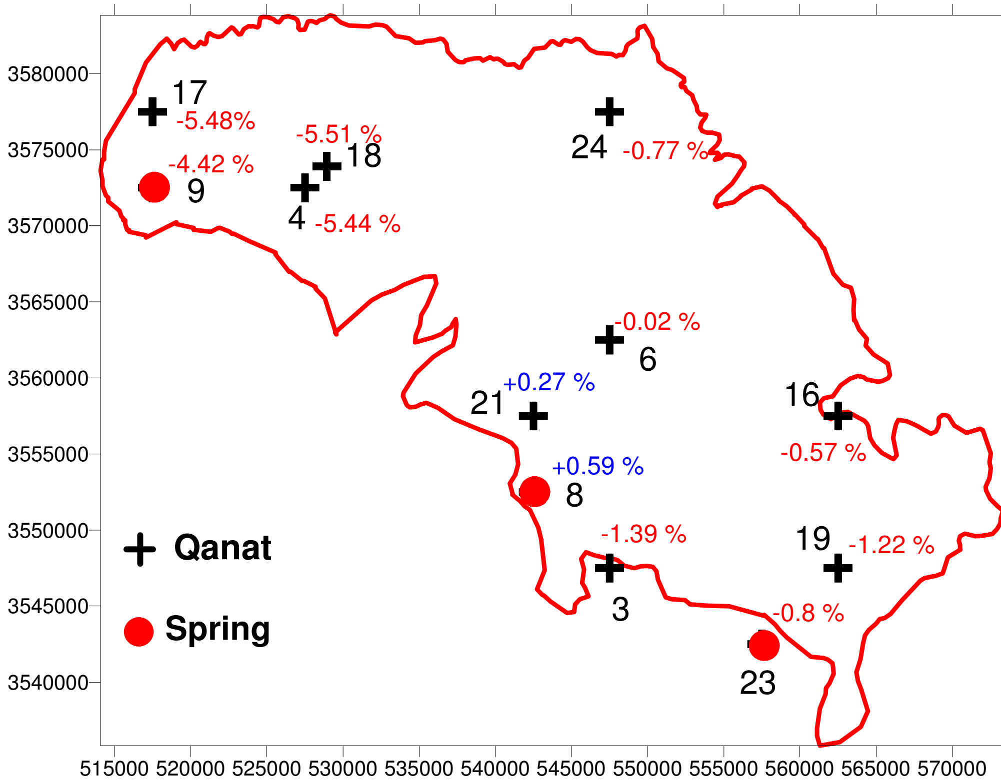

Fig. 16 Map of the representative Qanats and Springs in the Lenjanat Aquifer. The annual percentage change in discharge with respect to 1988 figures is also shown (see Table 5 above). It is clear that the northwestern part of the aquifer (17, 18, 9 and 4) is under higher stress than the eastern part. The aquifer area around 6, 21, 8 has probably received more recharge.

Fig. 16 shows a map of the representative Qanats and Springs in the Lenjanat Aquifer system. The annual percentage change in discharge with respect to 1988 figures is also shown (see Table 5). It is clear the northwestern part of the aquifer (17, 18, 9 and 4) is under higher stress than the eastern part. The aquifer area around 6, 21, 8 has probably received more recharge and shows a small positive trend over the last 10 years. From these figure it is clear that the large negative trend in the northwestern part of the Lenjanat Aquifer is caused by over-abstraction in this part of the aquifer, leading to a significant drop of the water table. In the other parts of the aquifer on average an annual decrease of 1% in discharge is observed.

Groundwater level changes

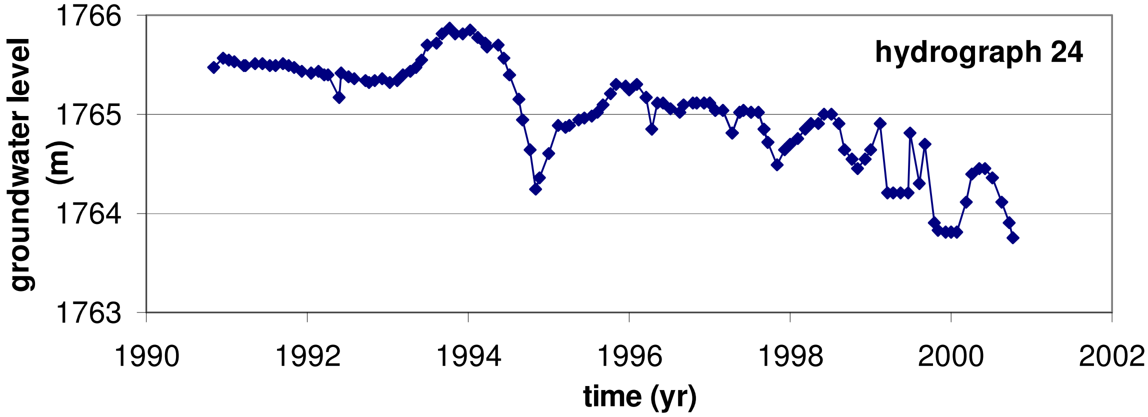

Fig. 17 Well hydrograph of observation well 18 (see Fig. 20 for position).

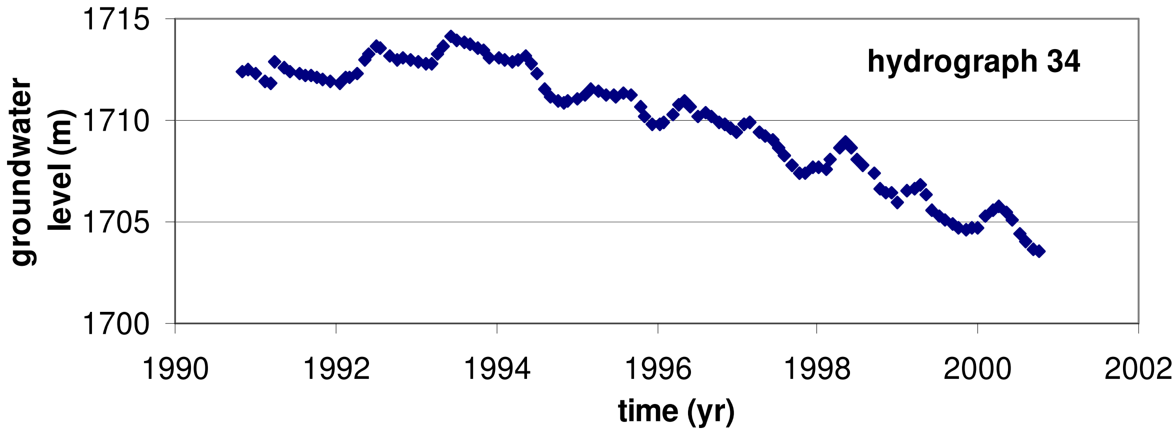

Fig. 18 Well hydrograph of observation well 27 (see Fig. 20 for position).

Figs 17 and 18 show hydrographs of observation wells 24 and 34 (see Fig. 9 for their positions. Their trend is clearly downward. Small fluctuations are caused by pumping and irrigation return flow. It is possible to determine the trend by a linear regression. In the case of Fig. 17 this appears to give good results. However, in the case of Fig. 18 the recession will be underestimated by linear regression because of the convex shape of

the hydrograph during this time period. The same is true for the hydrograph of well 47 (Fig. 19) This well is influenced by pumping while in the absence of pumping there is good recovery because of recharge from the alluvial fan. Since the response to pumping is rather large, the well seems to be in a (semi)confined part of the aquifer where storage coefficients are low.

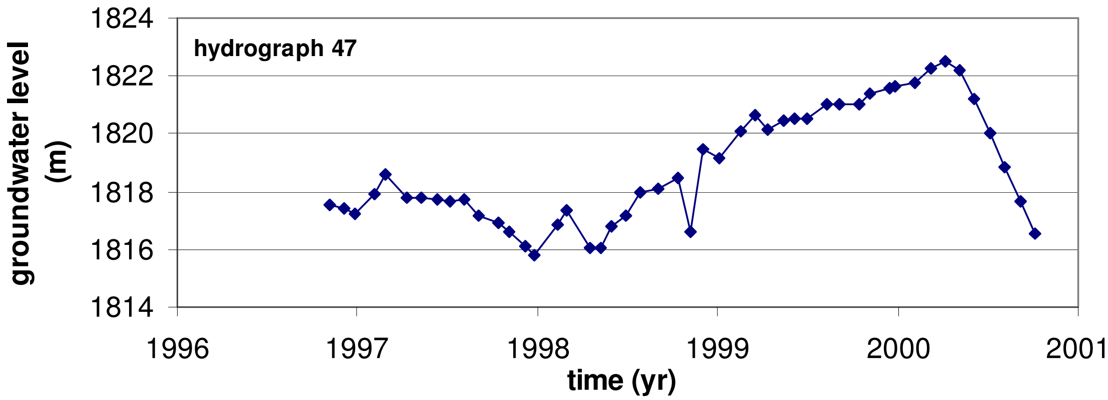

Fig. 19 Hydrograph of well 47 (see Fig. 20 for its location).

Nevertheless, the regression coefficients give a good approximation for the trend in the observations and they have been compiled in Appendix 1. Fig. 20 shows a map of the distribution of recession coefficients over the aquifer.

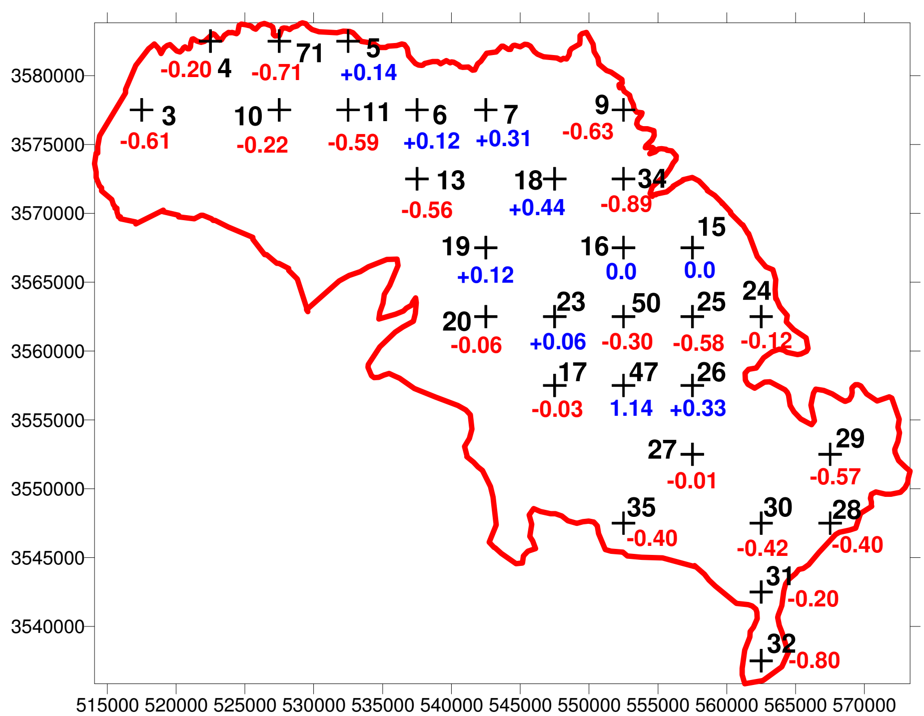

Fig. 20 The figure shows the aquifer with the observation wells discussed in section 5.

For each well 6 to 10 years of observations have been used to derive a recession value in myr^{-1}. The average recession coefficient is about 0.2 myr^{-1} corresponding to a drop in hydraulic head of about 2m in 10 years time. However, Fig. 20 shows that there are distinct differences in the different parts of the aquifer. The recession values in the northwestern part of the aquifer are high, confirming the discharge reductions of qanats and springs in this area. The eastern part also has high recession values, which is probably related to the high groundwater abstraction for irrigation in the northeastern

corner (see also Fig. 6). The wells in the central part of the aquifer, however, have low or even positive recession rates, indicating that this area receives sufficient recharge to balance the local abstraction.

7 Conclusions and Discussion

A groundwater modelling study was made in the Lenjanat District south of the Zayandeh Rud, to determine the magnitude of the main components of the water balance: recharge, abstraction by wells, qanats and springs, and groundwater losses to the Zayandeh Rud, if any. Determination of this last component is important in view of the general budget analysis of the river water for the main irrigation districts.

The Lenjanat Southern Plains Aquifer was delineated by interpretation of two ASTER images. It is surrounded by mountain ranges on the southern and eastern sides. To the north the aquifer is bounded by the Zayandeh Rud, while the administrative district boundary between Lenjanat and Ben Saman was taken as the western limit. The mountain ranges were taken as impermeable boundaries, while the Zayandeh Rud was considered a constant head boundary. Finally, because the groundwater flow lines are parallel to the western aquifer limit, it can be considered a no-flow boundary. Recharge is considered to take place as direct infiltration of precipitation, as lateral subsurface inflow and as mountain front recharge into the coarse colluvial cones at the foot of the mountains. It is assumed that the direct vertical recharge is much smaller than the lateral recharge across the aquifer boundaries.

The aquifer appears to consist of coarse sedimentary material with a succession of fine-grained sand-clay lenses leading to both unconfined and (semi)confined conditions. This was confirmed by the results of the pumping tests, which produced a wide range of transmissivity and storativity values. As a first approximation in the exploratory aquifer modelling undertaken here, the aquifer is taken as confined with constant thickness, while its hydraulic conductivity is considered variable.

The groundwater database consists of well level data for the period 1987-2001, detailed abstraction data for 1988, summary abstraction data for 1998 and discharge data for qanats and springs from 1988 to 2000. All well coordinates are recorded on the lower left corner of 5x5 km grid cells.

A steady-state model was developed using PMWIN (Chiang and Kinzelbach, 1998) as pre- and postprocessor for MODFLOW (McDonald and Harbaugh, 1988). The 1-layer model uses 500x500m cell size, with 4996 active cells with a total area of 1249 km^2. Confined conditions were assumed as an approximation to the mixed unconfined/confined behaviour of the aquifer. Calibration by adapting the recharge, abstraction and conductivity value maps, yielded a Root Mean Square Error (RMSE) of

22.6 m. This value seems acceptable in view of the large uncertainty in the well positions which may cause an error of ±25m in the water levels.

The steady state water budget shows that with a total recharge of 267 $MCMyr^{-1}$, a total abstraction (wells, qanats, springs) of 192 $MCMyr^{-1}$ and seepage into the Zayandeh of 76 $MCMyr^{-1}$ the components are in equilibrium (see also Tables 2 and 4). However, much depends on the aquifer's hydraulic transmissivity and conductivity values. If these decrease then so does the total recharge, and with that all components are changed. The three sets of pumping tests and the well logs only give an indication of the range in values.

If abstraction increases beyond the 192 $MCMyr^{-1}$ then according to the model a new steady-state can be reached with lower ground water levels, increasing the hydraulic gradients, and with increasing abstraction ground water levels near the Zayandeh will be drawn lower than the river level, leading to losses from the river to the aquifer.

The aquifer is not in steady state at present, which is shown by the decreasing groundwater levels and the diminishing discharge from the qanats and springs. Therefore clearly over-abstraction is taking place. The northwest and northeast corners of the aquifer are clearly areas in need of detailed attention, because well levels here are going down at a rate of 0.5 myr^{-1}, whereas the yield of springs and qanats is only 50% of what they were 10 years ago.

Acknowledgements

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Appendix 1 Observed groundwater levels (1997) and levels calculated by MODFLOW

Note:

1 Levels are averages of several wells in a grid cell

2 Position was moved from the lower left to the centre of the

num	xutm	yutm	gwlev	model	recession coefficients
	(m)	(m)	(m)	(m)	(myr^{-1})
3	517500	3577500	1819.88	1812.14	-0.1952
4	522500	3582500	1774.27	1762.90	-0.6098
5	532500	3582500	1700.80	1674.27	0.1404
6	537500	3577500	1695.94	1677.62	0.1162
7	542500	3577500	1670.44	1661.90	0.3064
9	552500	3577500	1634.30	1678.56	-0.6286
10	527500	3577500	1796.13	1756.86	-0.2238
11	532500	3577500	1731.34	1707.12	-0.5916
13	537500	3572500	1709.86	1733.74	-0.5594
15	557500	3567500	1733.08	1750.01	0.0025
16	552500	3567500	1763.84	1728.09	0.1229
17	547500	3557500	1909.41	1915.01	-0.0305
18	547500	3572500	1689.71	1691.73	0.4436
19	542500	3567500	1742.82	1737.60	0.1202
20	542500	3562500	1840.15	1783.08	-0.0590
21	542500	3557500	1918.66	1920.57	-
23	547500	3562500	1802.23	1838.14	0.0623
24	562500	3562500	1765.01	1772.77	-0.1249
25	557500	3562500	1750.85	1771.55	-0.5843
26	557500	3557500	1786.31	1796.17	0.3277
27	557500	3552500	1823.15	1832.89	-0.0101
28	567500	3547500	1834.70	1839.34	-0.3946
29	567500	3552500	1833.76	1831.37	-0.5689
30	562500	3547500	1880.83	1857.11	-0.4212
31	562500	3542500	1942.69	1958.22	-0.1967
32	562500	3537500	2007.77	1995.02	-0.7906
34	552500	3572500	1709.27	1706.65	-0.8830
35	552500	3547500	1885.46	1892.01	-0.3984
47	552500	3557500	1817.77	1858.43	1.1383
50	552500	3562500	1909.41	1891.48	-0.2987
71	527500	3582500	1706.66	1706.33	-0.7112

Appendix 3

The following reports have been published in the IAERI-IWMI Research Report series.

1. **Water Management for Sustainable Irrigated Agriculture in the Zayandeh Rud Basin, Esfahan Province, Iran.** (2000) H.R. Salemi, A. Mamanpoush, M. Miranzadeh, M. Akbari, M. Torabi, N. Toomanian, H. Murray-Rust, P. Droogers, H. Sally, A. Gieske.
2. **Exploring field scale salinity using simulation modeling, example for Rudasht area, Esfahan Province, Iran.** (2000) P. Droogers, M. Akbari, M. Torabi, E. Pazira.
3. **An overview of the hydrology of the Zayandeh Rud Basin.** (2000) H. Murray-Rust, H. Sally, H.R. Salemi, A. Mamanpoush.
4. **Groundwater chemistry of the Lenjanat District, Esfahan Province, Iran.** (2000) A. Gieske, M. Miranzadeh, A. Mamanpoush.
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6. **Sustainable irrigation and water management in the Zayandeh Rud Basin. Proceedings of Workshop in Esfahan, Iran, 19-21 November 2000.** (2001) Anonymous.
7. **Assessment of irrigation performance using NOAA satellite imagery.** (2001) P. Droogers, P., W.G.M. Bastiaanssen, A. Gieske, N. Toomanian, M. Akbari.
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