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Analysis of the groundwater resource decline in an intramountain aquifer system in Central Iran

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Abstract. The Shahrekord aquifer is located in an intramountain basin in Central Iran (90 km SW of Isfahan) and is the main resource of irrigation water for the intensively developed agriculture in the Shahrekord Plain. Early exploitation of the aquifer started back around 1950 but has intensified severely during the last decades. Irrigation water is provided by three means: spring water is tapped, water is pumped from around 650 wells and in historic times more than 100 karizes (or ghanats, deep underground channels that drain the water table and are accessed by shafts) were constructed and provide an additional source of water. However, groundwater levels have declined severely during the last decade, and although systematic piezometric monitoring already started in 1984, it stayed unclear whether the declining trend is related to increased water demand and exploitation or is due to climatic reasons, as around 2000 a severe drought lasted for three years. In this paper, exploitation and precipitation data are combined with the measured piezometric levels to analyse their relationship and help to understand the observed trend in declining groundwater storage. This aquifer is an example of a system that can easily deliver large amounts of groundwater because of a high transmissivity and considerable thickness, but has, for climatic reasons, a limited recharge. This imbalance makes the present level of exploitation unsustainable.

Keywords: groundwater, exploitation, Iran, sustainability

1. Introduction

Growth of the global and local economy, the standard of living and increase in population density, cause an increasing worldwide demand for useful and consumable water. Urban immigration had lead to larger demand for drinking water in cities, and an increased population must be provided with an increasing supply of food, which requires extension of agriculture, intensification of agricultural practices and more irrigation water. Especially in semi-arid and arid regions, demand often surpasses supply, as sources of water are limited due to climatological reasons. If groundwater is available, it is used at increasingly higher rates when surface waters become discontinuous in the seasonal dry periods. This is even more the case when longer multi-year droughts occur. Groundwater is then used as the main source of water and aquifers can become stressed to the limit. Pumped groundwater then comes from groundwater storage and not from groundwater recharge, and groundwater resources are being depleted. Recognition of groundwater depletion is a crucial step in evaluating the hydrodynamical status of reservoir systems, and can be started by simple analysis and correlation of precipitation, recharge and water level data. That is shown in this paper for the aquifer in the Shahrekord Plain in Central Iran, on which, until recently, there has been limited research into the functioning and evaluation of the aquifer system of this area (Radfar, 2009)

2. Description of the Shahrekord aquifer

2.1 Location

Shahrekord Plain (Fig. 1), covering about 650 km² and included in Shahrekord Basin (1211 km²), is located in the northeast of Charmahal and Bakhtiari Province in the west of Iran. It is situated in the northern UTM latitude boundary from 3555460 to 3603530 and eastern UTM longitude boundary from 457948 to 515864, around 90 km southwest of Isfahan.

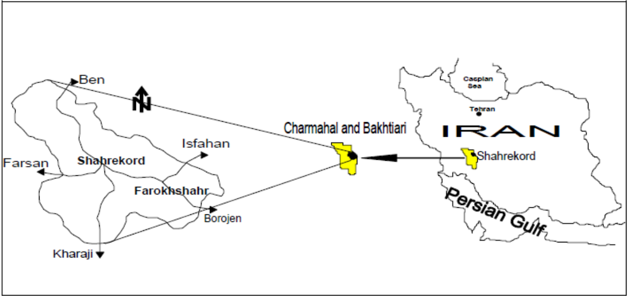

Figure 1: Location of the Shahrekord Plain and aquifer in Iran.

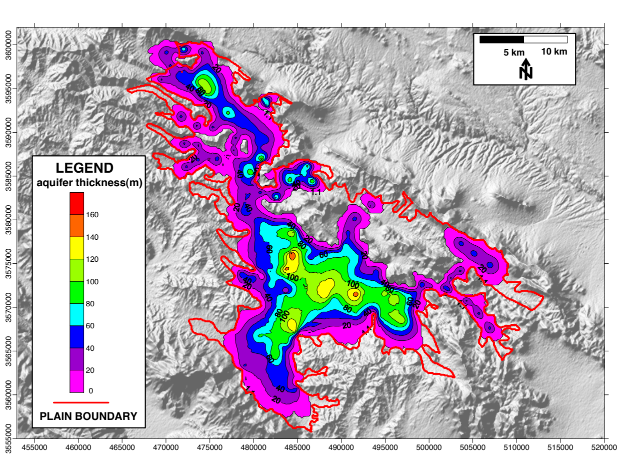

Figure 2: Thickness (in m) of the Shahrekord aquifer.

2.2 Geological setting en hydrogeological characterisation

The Shahrekord Plain is a south sloping plain at a height between around 2000 and 2300 m amsl. It is surrounded by hills and mountains which may reach elevations of up to 3000 m. The basement and surrounding mountain block is mainly limestone rock, which is, at least locally, karstified as some productive wells were drilled in there. The Shahrekord aquifer is developed in the sedimentary filling of the basin, which is mapped based on the descriptions of drillings and can reach a thickness of up to 100 m, locally even more (Fig. 2). The Tertiary-Quaternary aquifer system mainly consists of deposits eroded from surrounding mountainous areas and includes gravel, sandstone and siltstone. In the north part of the basin a semi-pervious layer divides the sequence in two distinct aquifers.

Generally the aquifer has a high transmissivity, several hundred m²/day, which supports high pumping rates. The sedimentary filling of the basin can be heterogeneous. Locally, at the surface, more silty sediments are found; these sites were known as "mud plains" in the past.

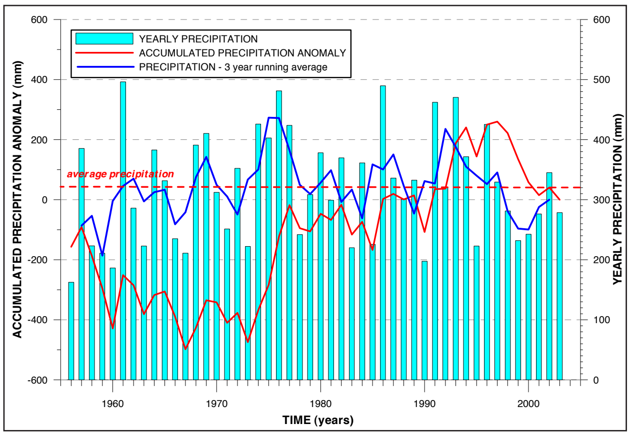

Figure 3: Yearly precipitation and accumulated precipitation anomaly (1956-2003).

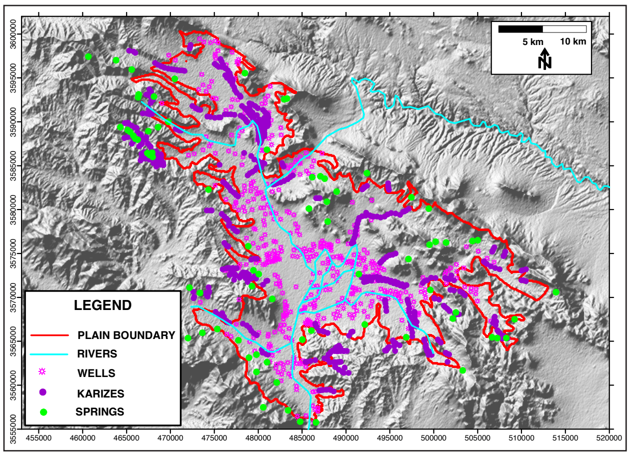

Figure 4: Location of wells, karezes and springs in the Shahrekord Plain.

3. Climate and groundwater recharge

Precipitation data are available for Shahrekord city from 1956 on in the Global Historical Climatology Network- Monthly version 3 dataset (Peterson & Vose, 1997; NOAA, 2011). Yearly precipitation in the period 1956-2003 (Fig. 3) averages around 320 mm. Wet years like 1991 and 1993 can have more than 400 mm, dry years between 200 and 250 mm. The climate has distinct wet and dry seasons. Precipitation falls almost exclusively in winter months, partly in the form of snow. Summers are very dry with nearly no rainfall at all.

The 3-year running average eliminates year to year variations and shows that the early nineties were rather wet, while around 2000 it was the driest time of the last 3 decades. This is also reflected in the accumulated precipitation anomalies, the accumulated sum of the differences between yearly precipitation and the long term average.

Radfar (2009) has calculated groundwater recharge in the Shahrekord Plain from precipitation and PET data, using a soil moisture balance model based on the Thornthwaite method (Thornthwaite & Mather, 1955). This approach has already been applied to other mountaineous aquifer systems (Walraevens et al., 2009; Bakundukize et al., 2011). Radfar found for the period 1989 to 2004 an average yearly recharge of 41 mm, or only 12.8% of the long term precipitation average. High recharge fluxes were calculated for the winters of 1991-1992 and 1992-1993. This is in agreement with the observed water table rise in these years. Also the winters of 95-96 and 97-98 had recharge events, but as piezometric levels were declining in this period, they are less pronounced in timegraphs. Dry years have no recharge at all. Normally this occurs every few years, but the summers of 1999, 2000 and 2001 form a three year continuous period without any significant recharge. The consequences are evident in all registered water level series: the aquifer system showed a dramatic drop in piezometric level. In addition to diffuse recharge in the plain itself, surface runoff from the surrounding mountains can enter the plain during rainy periods and add a locally distributed water source by streambed infiltration.

4. Groundwater exploitation

4.1. Water sources

The captured water has three distinct sources:

Springs

As the Shahrekord Plain is surrounded by mountains, spring water is directly captured. Surrounding the plain, 54 springs are used, another 22 springs are located within the plain itself. Their location is indicated in Fig. 4. The discharge of all springs was seasonally measured during one year, a subset was measured over the years. These long time series were used to extrapolate discharge rates for all springs based on a correlation analysis.

Karezes

The second main type of groundwater source is by karezes (Wikipedia, 2011) or “ghanats” (Bybordi, 1974) or “ganats” (Kevin, 2005). Karez construction is one of the traditional techniques leading out the groundwater to the ground surface by gravitational force (Karaji, 1966; Malekian & Pouraghniaei, 2001).

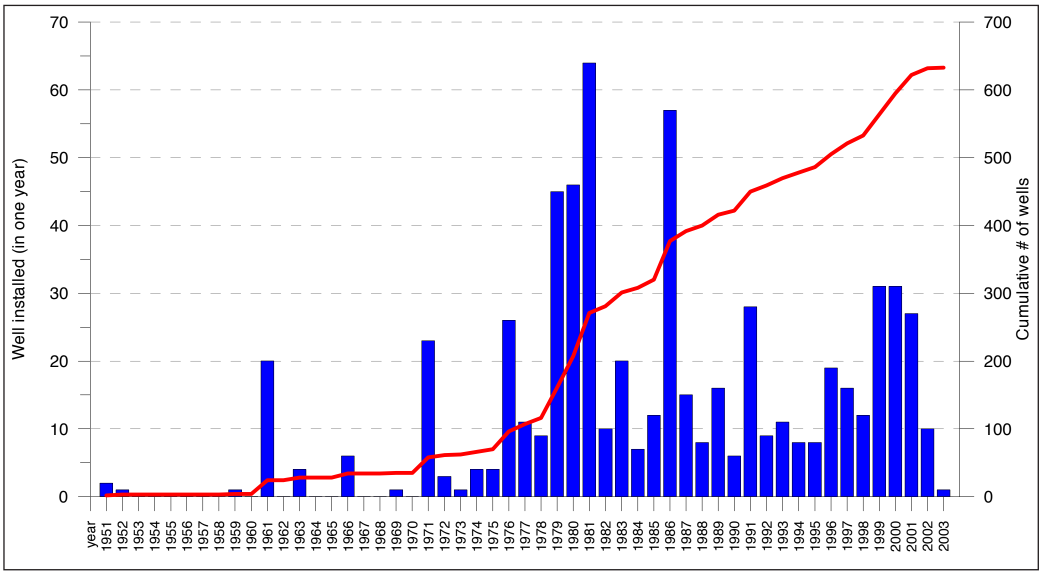

Figure 5: History of the number of drilled and installed wells in the Shahrekord aquifer.

A karez is a man-made, subhorizontal, gently sloping underground gallery, excavated into a sloping terrain, and which is connected to the surface by means of a series of vertical shafts, that are progressively deeper, until the final one. The final part of the gallery extends into the saturated zone, and the groundwater is led by the gallery to flow out gravitationally to the surface at the outlet. Formerly, there were 161 strips of karezes (Fig. 4) constructed in different parts of Shahrekord Basin, but exact data of historical construction are unknown. Nowadays just 130 strips out of 161 karezes are still wet and under groundwater exploitation perennially, also when the water is not needed. 76 strips of wet karezes out of 130 are situated outside the plain, the rest is developed completely within the plain. Discharge rate for the karezes was estimated by extrapolating detailed information for 8 and later 12 karezes to the other ones.

Wells

The oldest wells were traditional hand-made dug wells, with diameter around 1 meter, scattered in the cities and villages. Generally these wells were used for drinking water supply and they were discharged by wheels and man power. The first drilled well was constructed in 1951 and was equipped by gasoline motor pump and used for agricultural aims. Afterwards in order to increase cultivation, municipal uses and industrial activity in the area, well installation has been increased, reaching to around 650 wells in 2003, with different depths and discharge rates (Fig. 4). Estimating total well discharge rate was done by extrapolating detailed data of 10 and later 23 representative wells to the total number of installed wells. The evolution of the number of wells (Fig. 5) is a good indicator for the intensification of groundwater use.

4.2. Evolution of the groundwater exploitation

Yearly totals of the discharge rates of wells, karezes and springs are obtained by extrapolation of the measured discharges for a selected number of exploitations to the total known number of existing captures, as exact numbers are not available for all. This may have introduced some uncertainty on the numbers, and these totals should be considered as estimates, rather than registered values. Comparison of the contributions of the three water sources and total extraction rate (Fig. 6) is done on the basis of hydrological years, which last from October 1 till September 30 the next year. As aquifer recharge is limited to the winter period and groundwater exploitation is mainly concentrated in summer time, the hydrological year 1989-1990 includes the winter recharge and the exploitation of summer 1990 (not 1989). Some conclusions can be made from Fig. 6.

The total exploitation rate did not systematically increase over the period 1989 – 2004, but shows somewhat higher values in 1992/1993 and in the dry period 1999-2002. On average around 250 Mm^3/year is captured from the aquifer.

In 1992/1993 more water was taken from the karezes than from the wells, likely because they delivered more water in this wet period with higher groundwater levels. In the subsequent years the production of the karezes has decreased, while this loss was compensated by an equivalent increase in pumping rates.

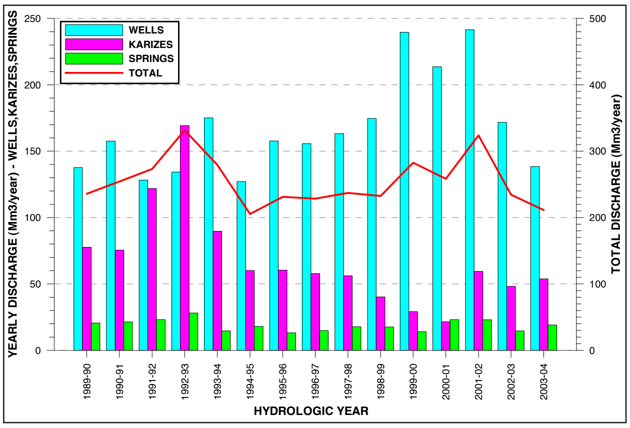

Figure 6: Evolution of the groundwater discharge rates of wells, karezes and springs.

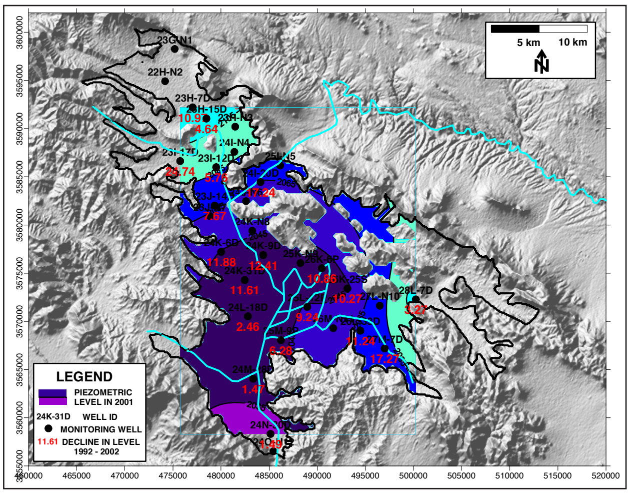

Figure 7: Location of the monitoring wells, piezometric levels in 2001 and groundwater decline between 1992 and 2002.

During the dry period of 1999-2002, the production of the karezes decreased dramatically because water levels dropped significantly. This caused an increased demand for pumped water, drilling of supplemental wells (see Fig. 5) and a severe increase in pumping rates. In these years 7 to 8 times more water was taken from wells than from karezes.

The contribution of spring water is small, less than 10%, and shows less variation over the years. This may indicate that the spring flow system is not strongly correlated with the piezometric levels in the plain. It may correlate with inflow from the surrounding mountain block and may depend on flow cycles in the karstified substratum.

5. Groundwater levels

5.1. Monitoring network

Systematic monitoring of groundwater levels already started in 1984 with installation of 15 observation wells. To further improve the piezometric network, another twelve piezometric wells were installed and equipped in 2002. Distribution of piezometric wells in the study area (Fig. 7) shows that most wells are located in the central part of the plain, few exist in the peripheral section. The wells are measured periodically, in the middle of the month. This allows recognition of both seasonal cycles and multi-annual trends.

5.2. Groundwater flow and evolution of groundwater levels

Because of the sloping topography, groundwater flow in the Shahrekord Basin is from north to south. Groundwater outflow

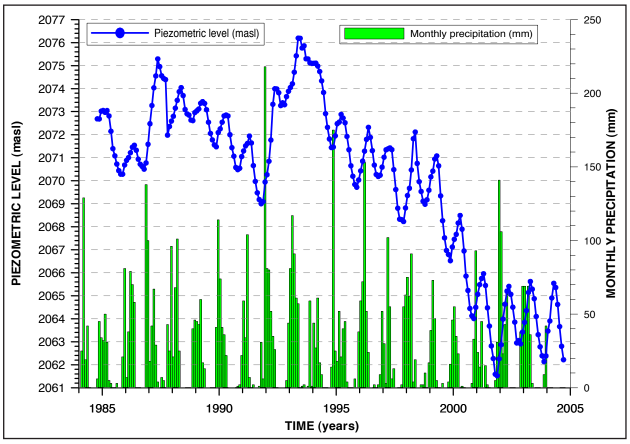

Figure 8: Monthly average piezometric level and precipitation in the Shahrekord Plain.

out of the basin is very limited as the outlet is a narrow topographical incursion. Apparently, before groundwater exploitation started, nearly all groundwater discharge occurred by drainage to the Shahrekord river. The Shahrekord Plain at that time was regularly wet and flooded as old inhabitants can recall. These "mud plains" have since long dried up. A piezometric map, based on the measurements of 2001 (year average levels in each observation well) is included on Fig. 7. That year the lowest levels were recorded (data until 2004). A head difference of around 100 m is found over a distance of ca 30 km (from north to south), so average hydraulic gradient is 1/300.

The general evolution of groundwater levels since 1984 was synthesized in the arithmetic average for all 15 observation wells, of the year averaged measurements for 1984 (Fig. 8). Although this value is only a statistical parameter and has no physical meaning, it reflects the overall hydrodynamic trend, and can also be considered as an indicator of the amount of groundwater that is available in the aquifer storage. The curve has two distinct characteristics. Seasonality (higher winter levels and lower summer levels) originates from meteorological conditioning: aquifer recharge can only occur in winter months as summers are absolutely dry with nearly no rainfall, and irrigation water needs for crops are limited to the dry summer period. The exact contribution of each of these two factors to the seasonal cycles is not yet quantified, but as the general trend in aquifer storage is downward, and groundwater discharge is concentrated in summer season, it may be assumed that the discharge flux in summer exceeds the recharge flux in winter time. This means that the seasonal cycles are mainly due to summer exploitation and to a lesser extent to winter precipitation. The second characteristic is the downward trend after 1995. Between 1984 and 1995 no systematic decline is observed, but large fluctuations do occur. The wet winter season of 1992-1993 has caused a significant increase in water levels and accordingly replenishment of the groundwater storage. But after 1995, a systematic lowering of levels is initiated, which is even more intensified around the year 2000. From 2002 on, levels seem to have stabilized, indicating no further depletion is continued, but no real recovery of the aquifer is apparent.

5.3. Reservoir storage and groundwater depletion

Correlation between water levels, groundwater storage and meteorological fluctuations (wet and dry periods) can be investigated by comparing time graphs of the average groundwater level and the accumulated recharge anomaly. This is the accumulated difference, of monthly and long term average recharge. Drier than average periods will lower the accumulated difference, wetter than average periods will raise it. Negative values indicate that accumulated recharge is still below the long term average, meaning the climate has not yet compensated for a previous dry spell, positive values tell the effect of a previous wet spell has not yet vanished. The results (Fig. 9) show that both curves are correlated as their fluctuations behave synchronically, but a distinction in two segments can be made. This is more obvious on a cross plot (Fig. 10). The graph clearly shows there is a strong (linear) correlation between both parameters, but the relation is different before and after 1995. Before 1995, corresponding water levels were ca 7 m higher (than after 1995) for the same accumulated recharge anomaly. This may be related to an, until now, unreversed depletion of the groundwater storage. Apparently, around 1995 the aquifer started to behave hydrodynamically different. As the slope coefficient of the linear relation becomes smaller in the second period (38 instead of 54 before 1995), it seems that the system becomes less sensitive to recharge anomalies. This may be related to the lowered position of the water table into deeper sediment layers with a somewhat higher value for the specific yield.

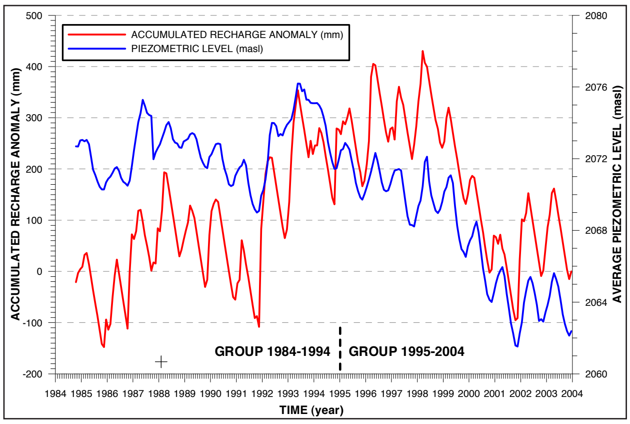

Figure 9: Evolution of the average piezometric level and accumulated recharge anomaly.

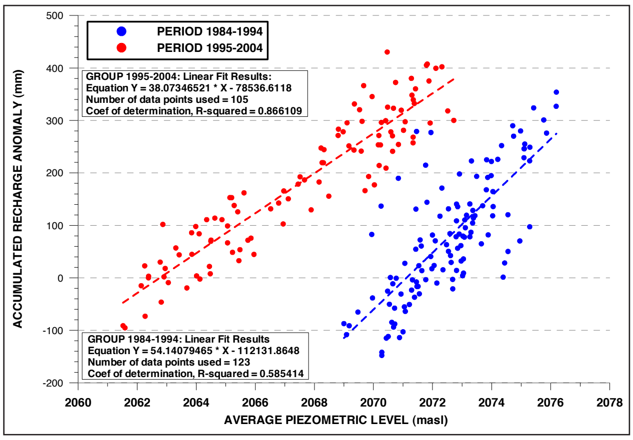

Figure 10: Cross-plot of average piezometric level and accumulated recharge anomaly.

6. Conclusions

The Shahrekord aquifer in Central Iran is an example of an aquifer system that has been strongly exploited as a source for irrigation water, as agriculture has developed strongly in the Shahrekord Plain. The aquifer itself is located in an intra-mountainous sedimentary basin with an areal extent of 650 km^2. Aquifer recharge is limited to around 41 mm a year or ca 26.6 Mm^3/year over the whole aquifer. Groundwater is captured from springs, 650 wells and more than 100 karezes, old long underground channels that tap water from the deep water table. Because of the considerable thickness of the aquifer (more than 100 m) and hence rather high transmissivity, large amounts of water can easily be pumped. This has led to a severe lowering of the piezometric levels since the mid nineties. The period 2000-2002 was exceptionally dry and no aquifer recharge occurred at all. Increased water demand, because of the continued drought, combined with absence of reservoir replenishment, is the cause of a dramatic drop in piezometric levels and groundwater storage in these three years. In most years, between 200 and 300 Mm^3/year of groundwater is extracted and average recharge is only 26 Mm^3/year, with some additional input by infiltration runoff from the surrounding mountains. Consequently, most of the pumped water is delivered from the storage of the aquifer system. Continued exploitation at the present level will be unsustainable.

7. Acknowledgements

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