Recharge origin, overexploitation, and sustainability of water resources in an arid area from Azraq basin, Jordan: case study

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Abstract The Azraq groundwater basin, found in Jordan, is an important resource for available water to the public. Its magnitude and value has been decreasing for the last two decades. The groundwater level has been declining on a yearly basis since the 1980s, and over-pumping, which has tripled since 1983, has led to the drying up of major springs in the 1990s.

Overexploitation is considered as the adverse effect on groundwater mass balance, where the abstraction increases yearly and beyond the safe yield. Over-pumping and irrigation activities cause groundwater to become more saline.

The isotopic composition of groundwater is divided into two groups. The first group is associated with EMWL, and the second with GMWL. The recharge origin of the first group, which includes the upper and middle aquifers, originate from outside the Azraq basin with a land elevation higher than 1150 m asl. The groundwater of the second group is considered palaeowater. No major recharge component is identified in the basin. Accurate and reliable scientific approaches are indispensable to better understand, plan and manage the groundwater resources.

Keywords Environmental isotopes; groundwater stratification; overexploitation; over-pumping; recharge; sustainability

Introduction

The Azraq location, geology and simplified cross section are presented in Figure 1. This area is a part of the desert where precipitation is scarce and limited, and is estimated to be less than 150 mm/yr. The basin covers an area of approximately 12 200 km^2, roughly 15% of the country.

Groundwater is the main water resource in the basin as surface water is limited to intermittent streams that are associated with rain during the winter time. The rainy winter season is between mid-October and the end of April.

The groundwater in the basin has been utilized since the 1970s through wells tapping various aquifers. In the early 1980s many wells were drilled by the government to provide more fresh water to supply the increased demand of other cities such as the capital, Amman.

The water abstraction has increased mainly from the upper aquifer over the years; the amount of pumping tripled between 1983 and 2003 (Al-Hadidi and Subuh 2001). This lowered the water level table of the upper aquifer in some wells up to 20 m. The observation wells in the basin demonstrate that the water table is declining at a rate of 0.3–0.8 m/yr (HCST 1999).

The over-pumping and return flow of the irrigation water caused the quality of the groundwater to deteriorate and has shifted the water type from fresh to brackish. The natural springs in the middle of the Azraq Oasis that discharged fresh, good quality water for thousands of years, dried out completely. Figure 1 shows the spring's location at a

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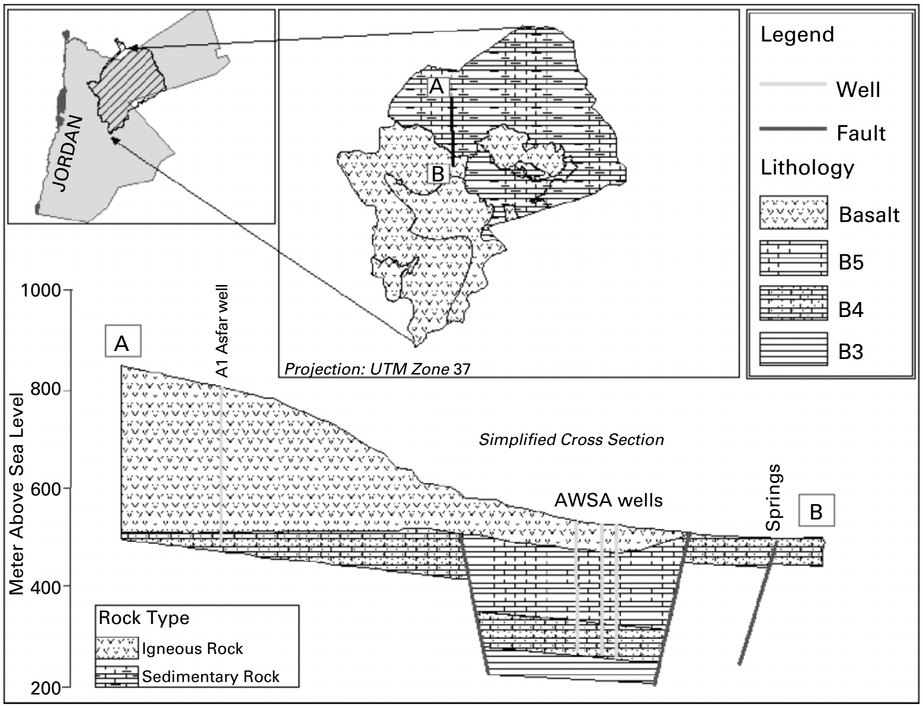

Figure 1 Location and simplified geological map of Azraq basin

contact fault, which hydraulically links the spring's discharge and groundwater of the upper aquifer.

The three principal aquifer systems are identified in the basin and range in age from Lower Cretaceous to Upper Cenozoic.

The groundwater from the three aquifer systems has been sampled for environmental isotopes and chemical analyses (Appendix 1).

The purpose of this work is to briefly discuss excessive groundwater withdrawal and its most apparent effects on the quantity and quality of water. The impact has been so great that the main springs no longer exist. Ignoring excessive groundwater withdrawal will continue to reduce the quality and quantity of groundwater resources, which will negatively impact the ecological setting of the entire basin. The environmental isotope will be used to improve the understanding of the recharge origin and infiltration mechanism of the three principal aquifer systems. In the discussion below a range of views and examples of corrective actions to contest overexploitation are discussed.

Methods and isotope analysis

Precipitation was sampled according to standard IAEA specifications from a rainfall station, yielding monthly composite samples. Groundwater samples were obtained from pumping wells and some were sampled more than once. The isotope analyses were carried out at the laboratory of the Water Authority of Jordan (WAJ) in Amman for chemical and isotopic analyses. Results are given in terms of per mil deviation from SMOW (δ‰), the value of the *d* parameter is also given in per mil ($d‰ = \delta D - 8\delta^{18}O$). Deuterium and oxygen-18 contents were determined by mass spectrometry with an overall precision of 1‰ and 0.15‰, respectively. Tritium was measured by the liquid scintillation counting of water previously enriched by electrolysis. These concentrations are expressed as TU and errors of measurement ± 1 are quoted for each tritium value (Appendix 1).

Geologic and hydrogeologic framework

The surface geology of the basin is unique and relatively uncomplicated. The northeastern part is dominated by basaltic lava originating from volcanic activity during the Tertiary Period. Basaltic flows cover about one-third of the total basin. The entire basin is dissected by a widespread valley network, which carries large quantities of unconsolidated materials and soil, which date back to the Quaternary. These alluvium deposits accumulated during floods and surface runoff following heavy rains. Figure 2 shows the “mud-flat” area which is located in the central depression of the basin. The thin desert soils of Azraq are highly saline, reflecting the area’s low rainfall and high rates of evaporation.

Rock outcrops in the basin range in age from Maastrichtian to Pleistocene. The sedimentary rocks consist mainly of limestone, chert, marl, clay and evaporites (Figure 1). A detailed geological description of the basin can be found in Bender (1974) and Sahawneh (1996). The basin is a tectonic depression associated with the Wadi Sirhan Graben; along the geological formations are sets of water-bearing layers. Three principal aquifer systems were identified in the Azraq basin (BGR and WAJ 1994):

1. Upper aquifer: this aquifer consists of basalt and limestone. It is exposed in the entire basin and consists of four water-bearing formations. The basalt extends from the center of the basin to the north. The thickness increases to the north and the basalt consists of six layers separated by volcanic ash, gravel, and clay (Bender 1974). Basalt is considered a good aquifer; the highest thickness of the basalt is estimated to be around 470 m. The aquifer is also under water table conditions, which is very deep in some locations, reaching up to 300 m.
2. Middle aquifer: this aquifer consists mainly of limestone and chert and is considered to be the most productive aquifer in the basin. This aquifer does not outcrop in the study area and is considered confined throughout the basin.
3. Deep aquifer: this aquifer consists of sandstone and does not outcrop in the Azraq area. It is considered a confined aquifer.

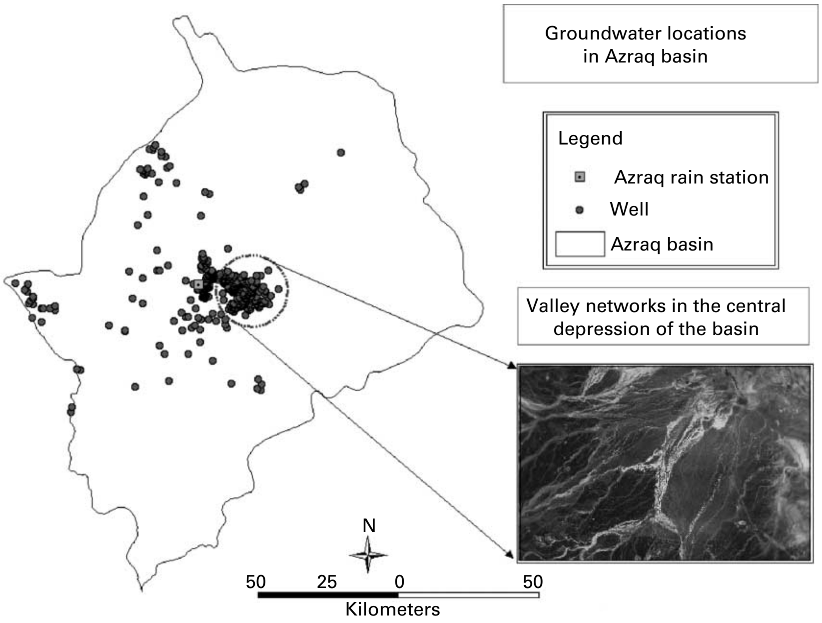

Figure 2 Wells and rain station locations in the Azraq basin

Four springs used to exist and discharged from the upper aquifer; however, the discharge ceased in 1990 due to over-pumping.

Terrain altitude model

The elevation of the terrain is an important factor for identifying the recharge altitude of the aquifer systems. The main point is to clarify if the rain from the Azraq basin can contribute to the recharge of the three aquifer systems. A simplified Digital Elevation Model (DEM) was produced in a Geographic Information System (GIS) environment (Figure 3).

The DEM consists of the basin land elevations, which originated from CAD files containing the basin elevation values. The DEM shows that the basin is irregular in shape and is a relatively shallow depression. It has a central playa, the elevation of which is about 500 m Above Sea Level (asl). Away from the central playa, altitude increases gradually to reach 900 m asl in the west. The highest elevation occurs in the north, and it is estimated to be around 1200 m as1. The basin's maximum elevation of 1550 m occurs outside the territory of Jordan and is in the Jebel Druze area of Syria to the north (BGR and WAJ 1994). The majority of the wells in the basin are located in the depression area between 550–600 m asl.

Results and discussion

Groundwater abstraction

The demand for more water resources for various purposes, mainly for domestic supply and agricultural activities, has been increasing for the last two decades. The water abstraction from the aquifers and the springs in the basin between 1983 and 2003 is presented in Figure 4. The total groundwater abstraction almost tripled in 20 years. The abstraction has increased from 21.57 million cubic meters (MCM) in 1983 to 59.3 MCM in 2003.

Figure 4 shows that the water abstractions increased on a yearly basis, most noticeably after the 1990s. At this period of time, an influx of immigrants from the surrounding areas fled to Jordan after the first Gulf War in 1990.

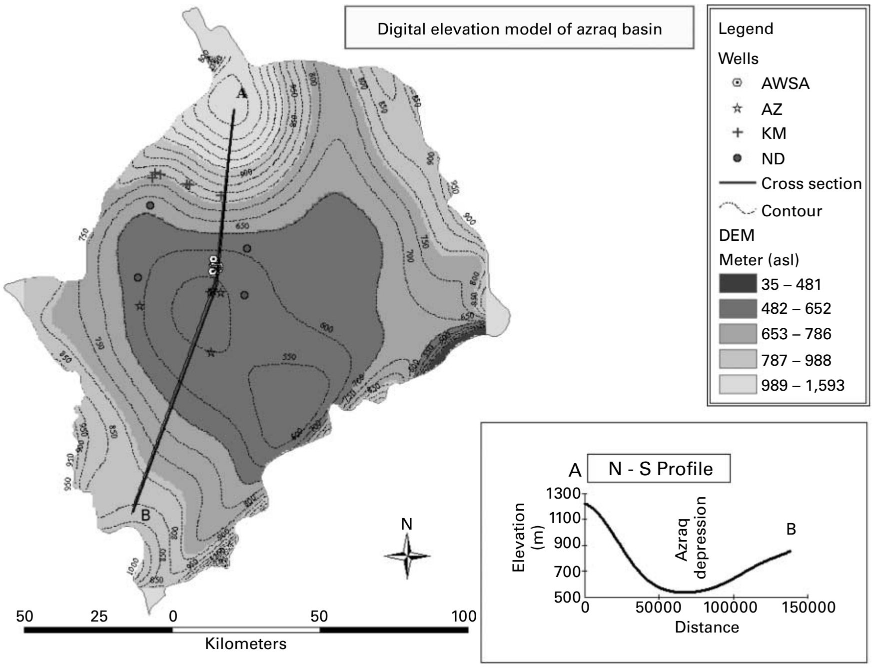

Figure 3 DEM and profile of the Azraq basin

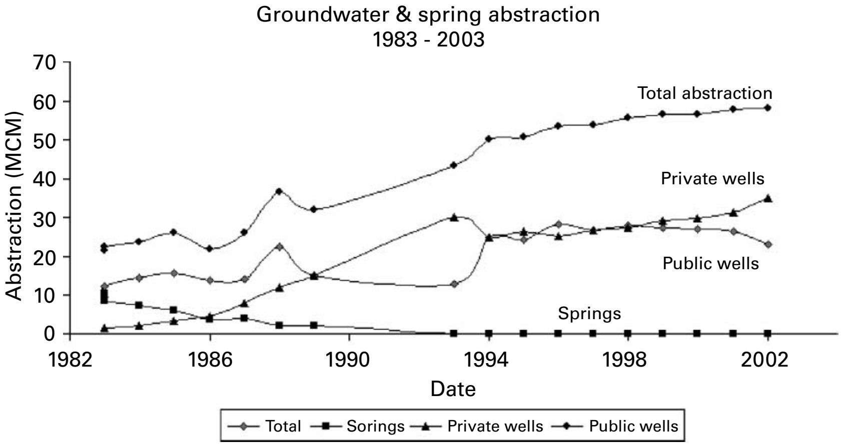

Figure 4 Groundwater and springs abstractions between 1983–2003

The amount of pumping exceeds the amount of recharge estimated by various authors (Barber *et al.* 1973; Agrar und Hydrotechnic GmbH 1977). In 1999 a mass balance of the groundwater of the upper and middle aquifers was calculated for the Azraq basin. The total withdrawal was calculated to be 53.9 MCM, while the recharge was estimated to be 24 MCM. This is overexploitation as the abstraction is greater than recharge by 2.25 times. The

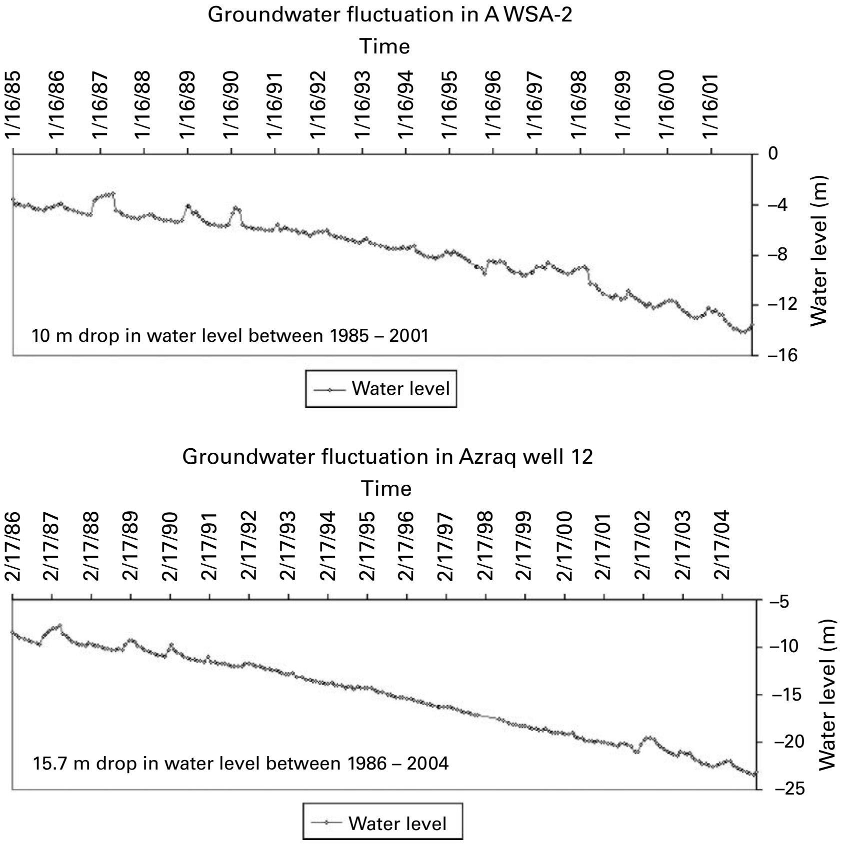

Figure 5 Groundwater fluctuation in two observation wells

groundwater was used for domestic (26.834 MCM), agriculture (26.299 MCM), industry (0.205 MCM), and other purposes (0.562 MCM). The injudicious practice of over-pumping has caused undesirable results from both environmental and hydrogeological aspects. Natural springs that sustained a balanced environmental condition have vanished, the groundwater table has declined severely, and the groundwater salinity has increased in certain locations. These negative results will be discussed briefly.

Before 1993 the major springs continually discharged a large quantity of water into the Azraq Wetland Reserve, creating a number of shallow pools and marshland extending up to 8 km^2. The pools were rare and considered the only permanent water within the desert that sustained a diversity of wildlife species. The springs dried out completely in 1993 due to heavy pumping of groundwater (Figure 4).

There are a very limited number of observation wells in the basin. The observation wells are mainly assigned to observe the water level of the upper aquifer. Azraq-12 and AWSA-2 are wells that have a total depth of 116 m and 195 m, respectively. The monitoring results of these two wells are presented in Figure 5.

The general trend indicates that the water level of the groundwater in the wells has been declining with no evidence of replenishment. Dottridge and Abu Jabber (1999) predicted that after 40 years a large-scale abstraction becomes impossible from the central Azraq basin.

The Azraq basin TDS increased in different locations and in different well fields heterogeneously. Water samples from two observation wells (AWSA-15 and AWSA-2) show a trend toward increasing salinity in time (Figure 6).

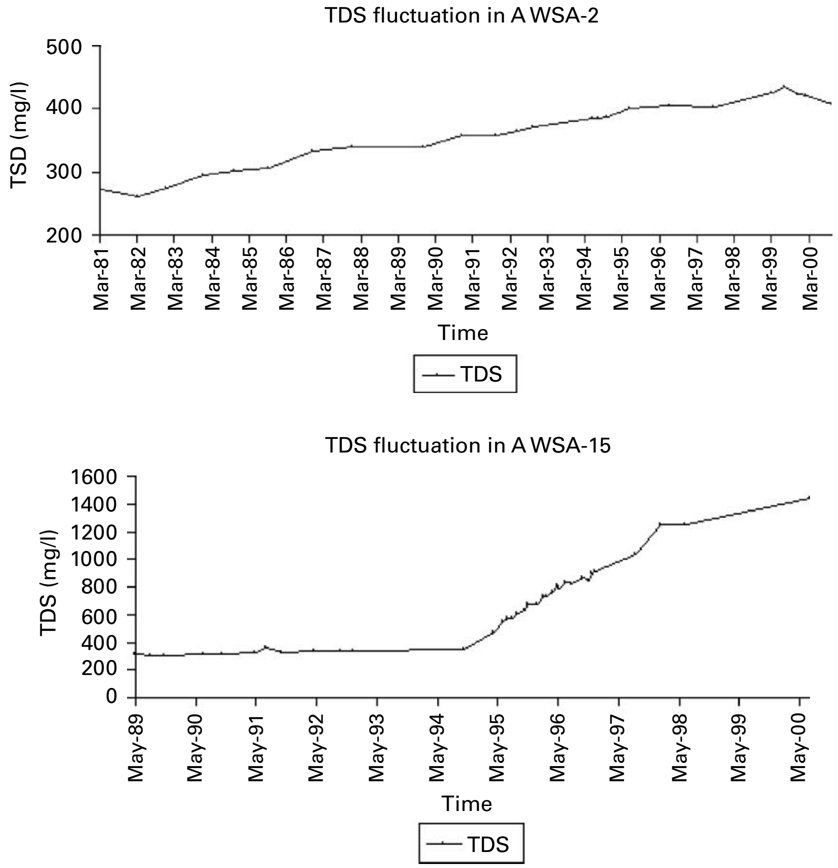

Figure 6 Groundwater TDS fluctuation in two observation wells

AWAS-15 confirmed a tremendous increase in salinity of about 300 mg/L per year between 1995 and 1999. Nevertheless, the observed salinity increase was recorded to be around 11 mg/L in AWSA-2. However, this could be due to a combination of the limited number of observation wells in the basin and irregular sampling of the two wells. It is clear from the two graphs that salinization is a great potential threat to the quality of groundwater.

Chemical classification of groundwater

The inorganic constituent concentrations in groundwater from the three aquifers are difficult to correlate with the quality of the precipitation water due to the lack of a complete chemical analysis of the rainwater. The chemical composition of groundwater is indicative of different mechanisms in the unsaturated zone during infiltration and residence time of the groundwater that is in contact with the permeable materials.

The chemistry of well samples is considered fresh as the TDS is less than 1000 mg/L with the exception of the deep AZ-1 well and a few groundwater wells tapping the upper aquifer. The chemistry was sampled more than once from some wells, and the Cl^- concentration showed a variation and an increase in time for some wells (Figure 7 and Table 1).

The average chemical composition for the three aquifer systems is listed in Appendix 1. Three chemical facies are identified in the groundwater: Na–Cl, Na–HCO_3, and Ca–Cl. The first two facies are related to the upper and middle aquifer, while the third is identical to AZ-1. The chemical composition reflects water rock interaction which consists of basalt and carbonates. The variation in Cl^- of some wells indicates an evaporation and irrigation return flow contribution. This is seen from relatively high NO_3^- concentrations (Table 1, Appendix 1).

The Na–Cl type of water is attributed to dissolution of evaporite minerals, such as halite and sylvite found within the lithology, from where the groundwater flows. It could also be due to salt deposits above the surface during the evaporation of surface runoff and irrigation water. The Cl^- versus Na^+ of the average samples is presented in Figure 8. The data plot more or less in a straight line with a high correlation coefficient ($R^2 = 0.92$). The slight departure from the regression line is identical for the two wells AZ-1 and NDW-5 tapping the deep aquifer. This suggests that sources of the ion other than halite (NaCl) are involved.

Recharge origin establishment through environmental isotopes

In an arid climatic zone, such as the Azraq region, annual rainfall variations and fractionation processes exert a great influence on the isotopic compositions of waters seeping into the subsurface (Bajjali 1990). The Azraq rainfall station, which is located in the oasis of the Azraq depression at 533 m asl was chosen to monitor the isotopic and chemical composition

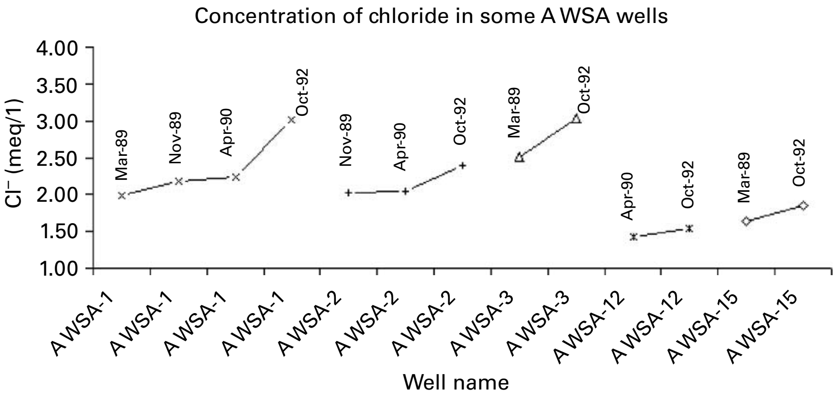

Figure 7 Chloride increase in time in some AWSA wells

Table 1 Cl^- concentration increase in some wells

Well	Date	Cl (meg/L)	NO_3 (mg/L)
AWSA-1	Mar 1989	1.98	5.1
	Nov 1989	2.18	5.2
	Apr 1990	2.23	4.8
	Oct 1992	3.02	5.1
AWSA-2	Nov 1989	2.02	5.0
	Apr 1990	2.05	4.4
	Oct 1992	2.40	5.4
AWSA-3	Mar 1989	2.51	5.1
	Oct 1992	3.03	6.6
AWSA-12	Apr 1990	1.43	9.8
	Oct 1992	1.55	10.2
AWSA-15	Mar 1989	1.63	11.6
	Oct 1992	1.86	12.8

of the rain, so it could be used as a guideline to evaluate the groundwater recharge processes in the study area.

The available isotope data from the rainfall station from 1967 to 1999 was used to provide averages based on monthly composite precipitation samples (Table 2).

The three samples of the Cl^- concentration demonstrated a broad variety, especially for the sample collected on January 1999. This sample could have been contaminated as the environmental isotope for the same sample does not show severe enrichment. The lack of major cations and anions make it difficult to attribute the high chloride levels to salt aerosols. Additionally, the Dead Sea and the Mediterranean Sea are relatively distant. Nevertheless, the Azraq soil is covered with superficial rock deposits and evaporite layers. Salt aerosol originating from evaporite minerals is a possibility and that depends greatly on wind velocity and direction. In general the precipitation in Jordan demonstrated a wide range of salinity of 25 mg/L to 140 mg/L between 1988 and 1989 (Bajjali 1990). The high salinity was linked to dust and proximity to major saline-water bodies to the west.

The main feature of Azraq precipitation is the wide isotope range observed in these waters, which is about 10‰ for $\delta^{18}O$ and 66‰ for δD (Table 2). However, there is no related discrepancy in the *d* parameters. The average *d* parameter (18.48‰) is found to be less than

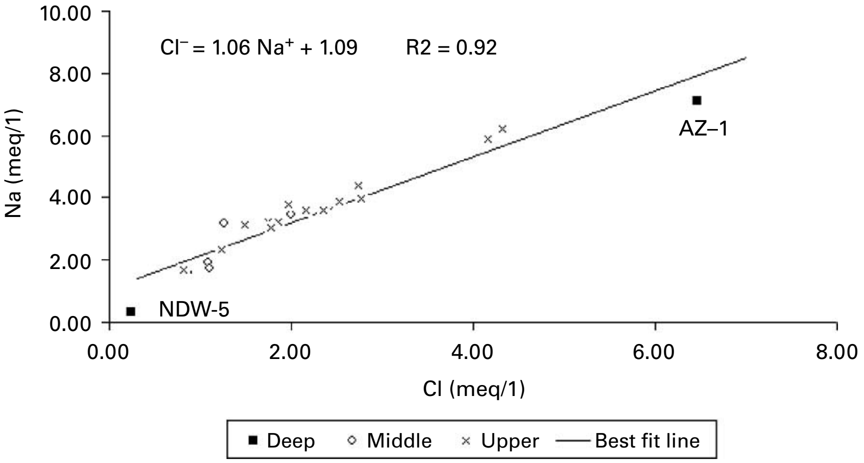

Figure 8 Relationship of chloride to sodium in the groundwater wells of the Azraq basin

Table 2 Stable and radioactive isotope in precipitation (rain samples > 10 mm)

Collection date	$\delta^{18}O \pm 0.15$	$\delta D \pm 1.0$	Tritium ± 1	Deuterium excess	Rain amount (mm)	Chloride
Oct 1967	−1.08	−11.5		−2.9	15.9	
Nov 1967	−1.77	7.4		21.6	13.2	26.27
Jan 1968	−9.77	−52.8		25.4	20.4	12.07
Dec 1987	−9.27	−52	13.4	22.2	17.9	
Jan 1988	−6.86	−28.9		26	25.2	
Mar 1988	−3.6	−15	12.7	13.8	21.3	
Jan 1989	−8.27	−45.4	9.4	20.8	32	
Jan 1990	−6.84	−40.2	NS.	14.5	15.6	
Feb 1990	−5.36	−20.9	NS.	22	22.7	
Oct 1990	0.68	12.9	6.2	7.5	15.7	
Jan 1991	−7.66	−35.8	7.5	25.5	46.9	
Mar 1991	−5.36	−25.9	6.4	17	28.6	
Jan 1998	−4.91	−25.2	6.9	14.1	27.2	
Jan 1999	−3.13	−12.3	12.9	12.7	13	136.32
Feb 1999	−1.72	3.7		17.5	12.6	
Jan 2005	−7.32	−39.6		19		
WMV	−5.63	−26.54	5.5	18.5	21.9	

the Eastern Meteoric Waters Line (EMWL) value defined by Gat and Carmi (1970), which is around 22‰. The value represents a kinetic effect when the water evaporates from the ground or sea surface and is defined as $d = \delta D - 8\delta^{18}O$ (Dansgaard 1964).

The monthly samples of the stable isotopes of the Azraq rainfall in conjunction with the Weighted Mean Value (WMV) of the Azraq and the Ras Munif of Yarmouk basin are presented in Figure 9. With no rain station in the Azraq to characterize the altitude effect, the Ras Munif station in Yarmouk basin was used in this context for appraisal and comparison purposes. The Ras Munif station is placed at 1150 m asl, which is comparable to the highest elevation in the Azraq basin. The isotopic composition of the Ras Munif is more depleted than the Azraq rain and its WMV is found to be $\delta^{18}O = -7.26$‰ and $\delta D = -33.20$‰

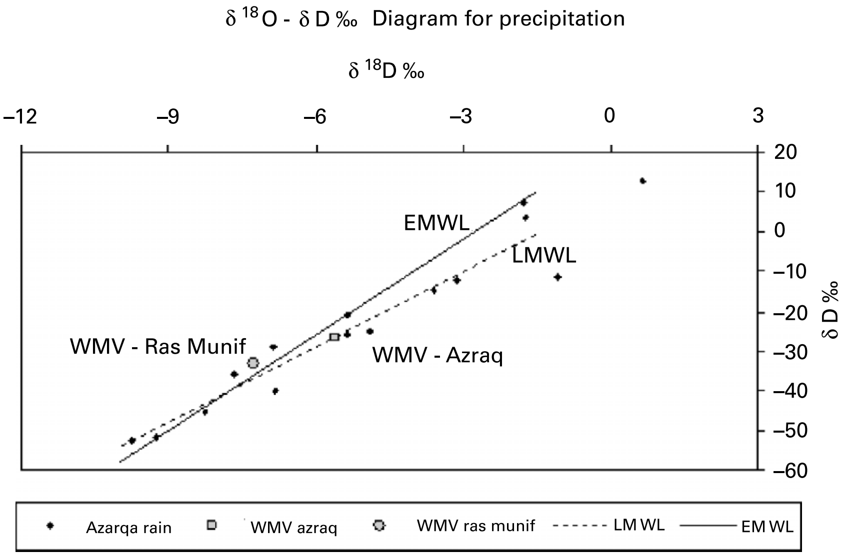

Figure 9 $\delta^{18}O - \delta D$ diagram of the precipitation in the Azraq basin

(Bajjali 2006). Due to the large world variation in isotopic composition of precipitation (Dansgaard 1964; Yurtsever and Gat 1981), the long-term WMV was taken as an input value to distinguish the isotopic compositions of the groundwater.

A seasonal variation was observed in the relationship between the δ^{18}O and δD of the Azraq precipitation (Figure 9). The data is presented by the Local Meteoric Water Line (LMWL), which indicates the origin of the air moisture. The LMWL was calculated to be

$$\delta D = (6.29 \pm 0.48)\delta^{18}O + (8.63.07 \pm 2.84) \quad (n = 15 \text{ and } R^2 = 0.92). \tag{1}$$

Figure 9 shows that the monthly samples at all the stations fall along the LMWL and the most divergent values relative to EMWL, usually enriched in both oxygen-18 and deuterium, are those of months with deficient rainfall (March 1989, April 1988, and May 1988). Apparently the amount effect and evaporation is the driving force for this variation. The WMV of the Azraq and the Ras Munif rain values are representing recharge altitudes of 533 m and 1150 m asl. The two WMVs are used as criteria to assess the groundwater recharge origin. The mean precipitation δ^{18}O values in 10 rainfall stations in Jordan from the same time period was found to decrease with an increasing altitude at a rate of about −0.1‰ per 100 m (Bajjali 1990). This signifies an altitude effect, which indicates that the oxygen isotope composition of precipitation undergoes fractionation during the moisture transfer from low to high altitudes.

An accurate calculation of the recharge altitude of the groundwater of the three aquifer systems is an essential step to verify the recharge origin, climate regime and residence time.

The stable isotope data of the groundwater of each aquifer, in conjunction with the WMVs of the Azraq and the Ras Munif precipitation, were plotted on the δ^{18}O–δD diagram (Figure 10). Some wells were sampled at different times for isotopic composition and revealed wide variations (Appendix 1). Therefore, the isotopic data of the three aquifer systems groundwater in Figure 10 represent the average isotopic composition of the samples.

The data of the upper and the middle aquifers are clustered more or less in one group with at least 1.7‰ and 11.1‰ differences in δ^{18}O and δD, respectively. The data are scattered broadly between the EMWL and GMWL and positioned along the evaporation line that originates from the EMWL. The location of the samples along an evaporation line can only be attributed to evaporation before infiltration.

Two mechanisms could be responsible for the slight evaporation of groundwater:

1. Return flow: some of the groundwater wells tapping the upper and middle aquifers are used extensively for irrigation year round. This practice makes the groundwater that has been used for agriculture become enriched with the isotopic composition due to

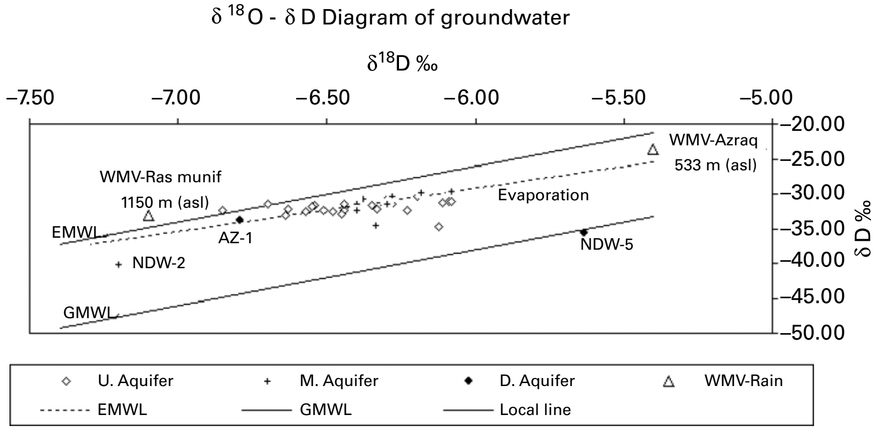

Figure 10 δ^{18}O–δD diagram of the Azraq groundwater and WMV of precipitation

direct evaporation. This excess water eventually returns back to the aquifer with the signature of the evaporation effects.

2. Groundwater stratification: the basalt aquifer is divided by six clay layers, so every layer represents a separate path to the groundwater from the recharge area to the point where the water is captured by drilling wells (Bajjali 1994). The heavy pumping in summer causes a greater mixing of water from the different permeable water-bearing formations. The middle aquifer has a hydraulic relationship with the basalt of the upper aquifer in certain locations of the basin and the isotopic composition of these wells could be mixing the two types of water.

The isotopic composition of the two wells, AZ-1 and NDW-5 tapping the deep aquifer is plotted in different locations on the $\delta^{18}O-\delta D$ diagram. AZ-1 is located within the upper and middle aquifer group but with slight depletion in isotopic composition. This can be attributed to the fact that the well is primarily penetrating the three aquifer systems and that only a small portion of about 40 m of the Deep sandstone aquifer has been penetrated. The NDW-5 is the only well that is located on the GMWL. The samples are characterized by the depleted isotopic signature typical of late Pleistocene (Lloyd 1980; Bajjali *et al.* 1997; Bajjali and Abu-Jaber 2001), which signifies a recharge origin other than the climate that currently dominates Jordan.

Without exception, all isotopic composition of groundwater of the three aquifer systems is more depleted than the WMV of precipitation in the Azraq Basin. This is a substantial indication that the groundwater cannot be recharged locally from rain originating from altitudes similar to the Azraq rainfall station. Therefore, the recharge for the aquifer systems in the Azraq basin should be originating from an area with an elevation higher than 533 m asl.

Furthermore, the evaporation line in Figure 10 is originating from a point at the EMWL, which is much more depleted than the origin of the WMV of the Ras Munif rain. This means that the recharge elevation for the upper and middle aquifer should come from an elevation area higher than 1150 meter asl.

Tritium radioisotopes may be used to estimate how long it took for a parcel of groundwater to travel from its recharge area to the measurement point. The groundwater in the Azraq Basin is completely intritiated, which simply indicates that the recharge took place before 1952. One well (F 1305) of the upper aquifer recorded a value of 1.6 TU, which signifies a very slight recharge in the post-nuclear period. The travel time of the groundwater of the Upper aquifer was estimated using radioactive carbon-14 techniques (Al-Momani 1996). The uncorrected age of water was obtained for two wells and estimated to vary between 11 000–14 500 yr. Thus, groundwater in the Azraq basin is beyond the range of tritium dating.

Overexploitation risks and corrective measures proposed

In order to achieve sustainable use and better management of groundwater various administrative and scientific steps should be taken.

The sharp lowering of the water table and the over-pumping has caused the Ministry of Water and Irrigation to enforce new regulations requesting that all owners of groundwater private wells install a flow meter in order to calculate the amount of water abstraction. This action is necessary to manage and control the amount of abstraction for each well in the basin and to observe the dynamic water level fluctuation. This approach is a move in the right direction. The continuous monitoring of the abstraction will gather reliable data for evaluating the aquifer mass balance and will predict any diverse effects from pumping and over-pumping. Over-pumping is a great concern for the government of Jordan, which issued a decree in 1988 (Dottridge and Gibbs 1996) to reduce the total abstraction from the Azraq basin by up to 20 MCM/yr. The abstraction decreased 18% in the governmental wells in the period of 1996–2002. However, the abstraction increased around 54% from private wells for the same period (Figure 4).

The Jordanian water act should clearly introduce the terms overexploitation and overpumping to protect the groundwater resources. Increasing the awareness of the importance of nature conservation and the demand for environmental impact assessments is necessary prior to the approval of any project related to water resources. Because groundwater in Jordan is owned by the government, it is suggested that mutual management of the groundwater is needed among different governmental institutions and especially between the WAJ and Ministry of Agriculture. This implies a more efficient use of the groundwater and improvements in the efficiency of irrigation methods, thus reducing evaporation losses and the cultivation of crops that demand less water.

A clear policy should be set regarding the priority of the groundwater use and its price. The price of the water should be based on criteria that will enhance and stimulate conservation.

It is necessary to educate the public about the importance of groundwater as the only source for drinking water, irrigation, and industry. It is important that the public realize that groundwater is not a resource that should be squandered simply because it is available in abundant quantities. Serious problems and issues such as water depletion and salinity are aggravated by the problems of overexploitation and contamination due to improper management of water resources.

Other important tactics are scientific approaches, which aim to promote research in order to contribute to a better understanding of the hydrogeological conditions of groundwater resources. More advanced techniques and approaches are required to assess the groundwater resources by using relatively affordable technology tools such as monitoring the groundwater, geophysical techniques, groundwater modeling, GIS, and remote sensing.

An efficient well monitoring network should optimally be designed throughout the basin for each aquifer in order to monitor the water table and the water quality. The availability of the monitoring data to the researchers and decision-makers will give a credible prediction of the long term effect of serious groundwater exploitation and provide flexible options for solutions.

A groundwater model for the upper and middle aquifers in the Azraq basin has been used to predict the future drawdown (Abdullah *et al.* 2000). The result shows that if the abstraction from groundwater reaches 68.1 MCM, the drawdown at the AWSA well field area will be 39 m. Such models can be improved significantly through obtaining an accurate database about the hydraulic parameters of the aquifers. The common practice in Jordan to obtain the hydraulic parameters is to conduct a pumping test relying only on one pumping well drawdown. This approach is not reliable or accurate to obtain the storativity value needed for running a groundwater model. Therefore, obtaining accurate data requires designing a pumping test with at least two wells; the first is the main pumping well and the second the observation well.

Artificial recharge is another method to improve the quantity and quality of groundwater. Various artificial recharge techniques have been discussed and used at various locations (Davis *et al.* 1964). Artificial recharge is an important avenue in arid areas for enhancing groundwater recharge by constructing injection wells or artificial dams (Bajjali 1997). In rainy seasons across valleys, frequent large quantities of surface water runoff in the Azraq basin spread on the valley network (Figure 2) beds flowing into the desert areas or impermeable plains. The surface runoff would be lost because of infiltration capacity in the area being insignificant relative to the volume of flowing surface water and evaporation. Constructing artificial dams across some valleys to recharge aquifers spread on the valley beds is an effective alternative way to use the water behind the dams. Artificial dams in arid areas such as Oman have proved to be a successful method to improve the quantity and quality of water (Bajjali 2005). In addition, treated wastewater can be used as an artificial source to improve the highly salinated shallow aquifer and eventually limit its use for certain crops of restricted irrigation.

Remote sensing and GIS techniques have been used successfully for various purposes in arid environments all around the world. The Azraq basin was studied using Synthetic Aperture Radar (SAR) to test the potential of such imagery for natural resources management in an arid environment (water harvesting, geological, structural, and hydrological mapping) and to evaluate the utility of data fusion for structural analysis in the basin (Saint-Jean *et al.* 1995).

GIS is an excellent tool for spatial analysis and for providing important objective information for decision-makers. GIS has been used extensively to study diverse issues related to groundwater resources from simple mapping to groundwater analysis and modeling. A groundwater vulnerability map was created using the DRASTIC model in the Azraq basin by incorporating depth to groundwater, estimated recharge, aquifer media, soil media, topography, and the impact of the vadose zone (Al-Adamat *et al.* 2003). The vulnerability map showed that around 84% of the study area was classified as being at moderate risk while the remainder was classified as low risk.

These different scientific approaches will be devoted to extract practical lessons to discuss practical ways of putting sustainable groundwater management into action. In addition to that, it could result in the creation of strategies for sustainable development and management of the resource.

Conclusions

The overexploitation of groundwater is defined as a condition in which abstraction is greater than recharge. The shortage in water resources, a great demand for supplying fresh water, insufficient knowledge of the hydrogeological conditions of the Azraq basin and lack of proper management led the decision-makers to overexploit the groundwater without an acceptable policy or plan. Overexploitation causes negative consequences on the groundwater quantity, quality and the natural wetland.

The abstraction of the groundwater has increased on a yearly basis and pumping almost tripled in twenty years between the period 1983–2003. This performance has resulted in the problem of groundwater overdraft as a result of which constant depletion of water levels has been observed in many monitoring wells tapping the upper aquifer. In some wells the water level declined up to 20 m and caused the natural springs that sustained a diversity of wildlife to vanish completely.

The groundwater salinity of the aquifers increased significantly and in some wells the salinity increased on a yearly basis and the quality shifted from low salinity fresh water to more salinated water.

The isotopic composition of the groundwater reveals that the recharge origin of the upper and middle aquifers is located at an altitude much higher than the altitude of the Azraq basin, which signifies a recharge origin from outside the basin. The tritium level revealed that the local recharge is trivial and constrained to the upper shallow alluvium aquifer. The groundwater of the Deep Kurnub sandstone aquifer is classified as paleowater and was recharged during the Pleistocene Epoch.

Overexploitation can be avoided by constraining actions related to management, monitoring information, and proper hydrogeological knowledge. Appropriate legislative measures should be taken to regulate irrigation, cropping, and pumping patterns. Artificial recharge can be carried out to control the depletion of water levels. Increased awareness can also be achieved by initiating an educational program to inform water users in the governmental and private sectors of the developing situations and methods to prevent further consequences.

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Appendix 1 Chemical and isotope data and aquifer type of the wells

Code	Tritium TU ± 1	$\delta^{18}O$ ± 0.15	δD ± 1	TDS mg/L	Ca mg/L	Mg mg/L	Na Mg/L	K mg/L	HCO_3 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L
Upper aquifer												
F 1021	0.0	−6.55	−31.80	1313	44	22	438	31	159	235	385	0.0
F 1022	0.1	−6.11	−31.20	353	15	7	83	7	116	49	70	7.3
F 1028	–	−6.23	−32.40	694	38	19	160	10	159	54	246	8.4
F 1029	–	−6.33	−32.20	436	18	11	102	7	137	49	102	9.6
F 1030	–	−6.44	−32.00	509	31	12	117	7	126	47	157	10.7
F 1031	0.3	−6.44	−32.30	147	0	0	67	6	0	0	69	4.3
F 1033	0.0	−6.63	−32.20	285	29	5	50	4	128	25	37	8.5
F 1034	–	−6.51	−32.30	425	15	9	106	7	127	55	94	11.3
F 1035	–	−6.28	−31.50	339	20	11	68	5	120	39	63	13.5
F 1036	0.0	−6.45	−32.90	–	–	–	–	–	–	–	–	–
F 1037	0.2	−6.48	−32.50	466	16	11	114	7	134	56	119	9.7
F 1038	0.0	−6.54	−31.70	377	31	3	82	6	126	42	74	13.6
F 1039	0.0	−6.30	−30.90	663	33	21	159	13	115	69	246	7.9
F 1040	–	−6.70	−31.50	533	23	14	124	13	133	74	143	9.6
F 1053	0.6	−6.91	−35.40	1004	93	33	163	18	272	195	229	0.7
F 1054	0.1	−6.44	−31.50	438	21	11	99	7	115	58	120	6.3
F 1058	0.0	−6.40	−31.30	–	–	–	–	–	–	–	–	–
F 1059	0.7	−6.20	−32.70	552	26	15	129	9	126	68	167	12.1
F 1060	0.0	−6.41	−30.60	392	12	8	103	0	124	36	106	3.0
F 1062	0.0	−6.08	−31.00	291	12	7	74	0	101	33	55	9.9
F 1091	0.0	−6.57	−32.50	310	13	7	71	0	129	27	59	4.0
F 1305	1.6	−6.31	−32.00	345	16	7	81	8	101	46	77	10.2
F 1310	0.0	−6.16	−30.30	264	14	14	44	6	103	26	45	13.0

Appendix 1 *continued*

Code	Tritium TU ± 1	$\delta^{18}O$ ± 0.15	δD ± 1	TDS mg/L	Ca mg/L	Mg mg/L	Na Mg/L	K mg/L	HCO_3 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L
F 1312	0.0	− 6.38	− 30.70	233	14	11	37	5	110	13	33	11.6
F 1350	0.0	− 6.15	− 34.60	380	11	14	171	5	–	–	175	3.5
F 3946	0.2	− 6.88	− 32.60	–	–	–	–	–	–	–	–	–
Middle aquifer												
F 1123	0.0	− 6.23	− 29.40	290	19	15	45	7	106	17	67	13.9
F 1124	0.0	− 5.59	− 29.80	–	–	–	–	–	–	–	–	–
F 1125	0.0	− 6.42	− 29.60	270	12	1	70	6	92	35	44	9.8
F 1125	0.6	− 6.45	− 31.90	270	12	1	70	6	92	35	44	9.8
F 1305	–	− 6.40	− 31.40	345	16	7	81	8	101	46	77	10.2
F 1312	0.8	− 6.18	− 29.90	233	14	11	37	5	110	13	33	11.6
F 1350	0.0	− 6.31	− 34.60	380	11	14	171	5	–	–	175	3.5
F 1358	–	− 6.35	− 31.70	14	1	1	2	0	–	–	1	9.7
F 1360	–	− 7.30	− 40.20	67	7	10	13	0	6	4	18	8.5
Deep aquifer												
F 1053	0.0	− 6.70	− 31.70	1004	93	33	163	18	272	195	229	0.7
F 1354	0.0	− 5.63	− 35.60	53	8	3	8	0	4	7	9	15.3