Hydrochemical Evaluation of Groundwater in Azraq Basin, Jordan Using Environmental Isotopes and GIS Techniques

William Bajjali[1] and Khair Al-Hadidi[2]

1 University of Wisconsin, Department of Biology and Earth Sciences, Superior, WI 54880
2 Water Authority of Jordan, Director of groundwater Basin Directorate, Amman, Jordan

Twenty-Fifth Annual ESRI International User Conference - San Diego, California, July 25–29, 2005

Paper UC2359
http://events.esri.com/uc/2005/papers/index.cfm

Abstract

The stable isotopic and chemical composition of precipitation and groundwater of three aquifer systems were studied in the Azraq basin in Jordan. The basin is located in the north-east of Jordan and is considered an important source of fresh water for domestic supply, agriculture, and salt industry. Quantity and quality of groundwater has been deteriorating for the last two decades at various well field locations due to over-pumping and return flow of agricultural water. The water level of the Upper aquifer has declined several meters beyond the initial static water levels and there is no sign of replenishment. The groundwater level has declined on a yearly basis since the 1980s, which caused the major springs in 1990 to cease completely.

The isotopic composition of groundwater clustered into three different groups associated with the Upper, Middle, and Deep aquifers respectively. The recharge origins of the first two groups are originating from an area with an elevation much higher than the terrain elevation of the Azraq rainfall station. The recharge origin of the Middle aquifer is higher that the elevation of the Upper aquifer and originates from altitude higher than 1150 meter asl. The location of the water samples of the first two groups along the EMWL demonstrate that the time of recharge is under similar climate conditions that exist currently in Jordan. The wide variation of isotopic composition of the groundwater analyzed frequently from the Upper and Middle aquifers are attributed to water stratification within the water bearing formations.

The third group of groundwater is associated with GMWL, which signifies the old origin of recharge in the Pleistocene epoch.

The wide range of groundwater facies and different types of water are identified. The groundwater is considered alkaline earth water with prevailing chloride concentration.

Introduction

The Azraq basin is located in the north-east of the country and bordering Syria and Saudi Arabia (Fig.1). The Basin is considered part of the desert where the amount of precipitation is scarse and limited and estimated to be less than 150 mm/year. The Azraq area is around 17,000 km^2, which account for about 15% of the country.

The main water resource in the basin is the groundwater. 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 Azraq Basin is an important groundwater source for domestic water supply and agriculture. The groundwater in the basin has been utilized since the seventies through wells tapping various water-bearing formations. Many well fields were drilled in the Upper aquifer in the early eighties to provide more fresh water to supply the increased demand of other cities in the country, such as the capital Amman and Zarqa. This practice negatively affected the whole hydrogeological setting of the basin.

The water abstraction has increased mainly from the Upper aquifer through the years. The amount of pumping has tripled between 1983 and 2003, where the abstraction increased from 21.57 MCM to 59.3 MCM respectively (Al-Hadidi and Subuh 2001) The water level declined dramatically in some well fields, up to 20 meters. The observation wells in the basin demonstrate that the water table is declining in the range of 0.3 to 0.8 m/y (HCST, 1999).

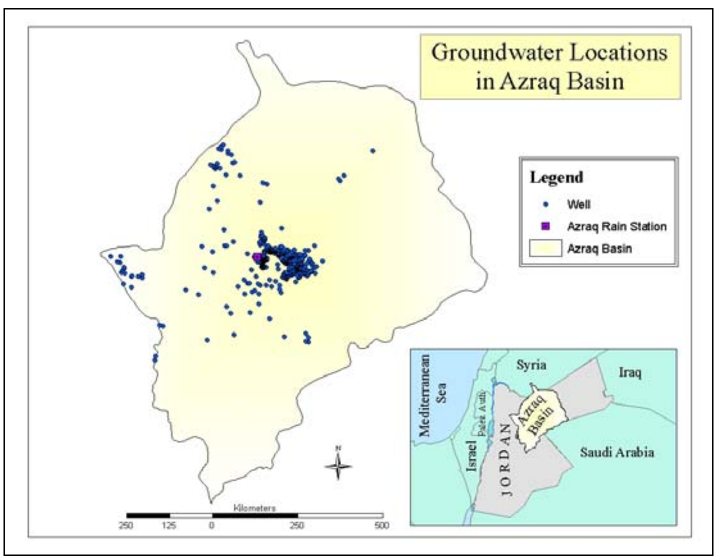

Fig. 1 Location of Azraq Basin in Jordan

The groundwater had been of excellent quality during the seventies. Due to the extensive pumping and return flow of the irrigation water, salinity in certain areas shifted from fresh water to saline groundwater.

The four natural springs in the middle of the Azraq oasis that discharged fresh, good quality water for thousands of years, dried out completely. This was due to over-pumping and lowering the water table of the Upper aquifer. Figure 2 shows clearly that the springs are located at a contact fault that facilitates the groundwater from the Upper aquifer to discharge through this fault as springs.

Three aquifer systems are identified in the basin: Upper aquifer (Basalt and Carbonate), Middle aquifer (Carbonate) and Deep aquifer (Sandstone). The three aquifer formations are ranging in age from Aptian of Lower Cretaceous to Quaternary of the Upper Cenozoic.

Many wells tapping the three aquifer systems in the basin have been sampled for chemical and environmental stable and radioactive isotope analyses (Appendix 1). The isotope of the Azraq precipitation was also sampled and analyzed. The results of the analyses was integrated into the GIS environment and interpreted.

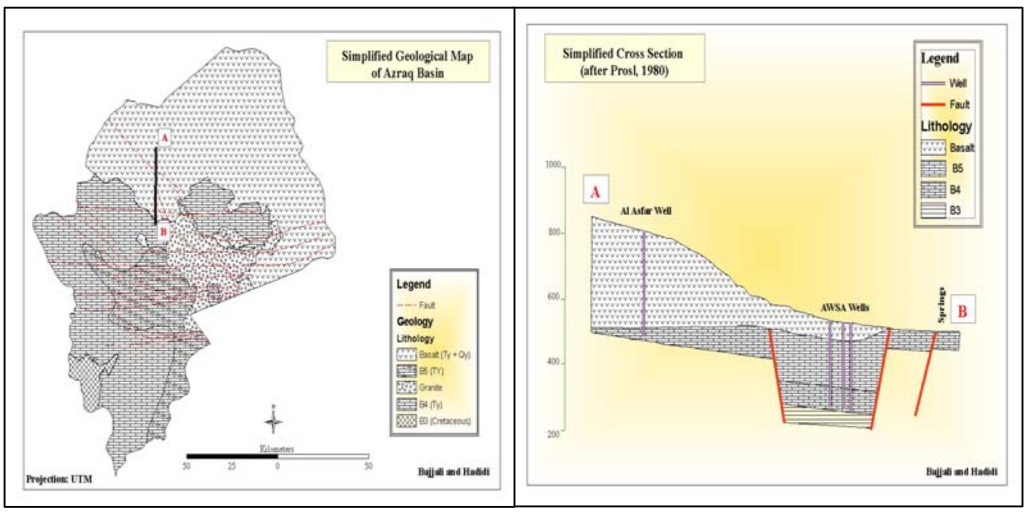

Fig. 2 Simplified Geological Map of Azraq Basin

Methodology

The geographic extent of the Azraq Basin is from approximate longitude 36^0 33' 36" to 37^0 32' 9" and from latitude 30^0 52' 22" to 32^0 27' 40". The isotopic and chemical data have been sampled from the groundwater wells and springs for many years in order to establish the relationship between the three aquifer systems, recharge area, mechanism of recharge, and quality of groundwater (Fig.1). The isotopic composition of the Azraq precipitation was also sampled on a monthly basis. The stable isotopes of oxygen ($\delta^{18}O$) and hydrogen (δ^2H), the radioactive isotope of hydrogen (^3H), and the chemical analysis were used in this study. Samples from drilled wells were taken after the pumping of wells for 10-20 minutes and some wells were sampled more than once. Samples were delivered on the same day to the Laboratory of Water Authority of Jordan (WAJ) in Amman for chemical and isotopic analyses. Deuterium and oxygen-18 contents were determined by mass spectrometry with an overall precision of 1 ‰ and 0.15 ‰, respectively, while tritium was measured by 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. The values of stable isotopes are expressed conventionally in delta (δ) notation as per mil deviation from the V-SMOW (Vienna Standard Mean Ocean Water).

The groundwater wells with the chemical data associated with them were recorded as a location in a real world plane coordinate (UTM zone 36). The original chemical data were in MS-Excel format. The data were converted into a database format and then integrated into ArcGIS as a shapefile format.

The groundwater wells, basin, geology, and structure were created from DWG format (AutoCAD). The data were first edited in AutoCAD and then integrated into ArcGIS.

GIS approaches to prepare the data for analysis

A variety of GIS approaches have been used in this study to integrate the different databases into the GIS environment. The digital data used in the study was originally incorporated primarily from AutoCAD format and Excel database. The following is the most important GIS steps that have been taken to perform the analysis:

1-CAD format conversion: Some of the data was converted into shapefile format in order to be fully usable in the GIS environment. Some of the digital CAD files contained blocks, which are irrelevant to any GIS data organization and interpretation. These blocks were removed and meaningful themes with relevant attributes were created. A few of the original digital CAD files were registered in a false table coordinate. The files were transformed from the false coordinates into UTM zone 36 in order to make them usable in the GIS analysis.

2-Database integration: The Azraq basin has many groundwater wells drilled all over the catchment area. The wells with the relevant hydrological data are documented at the Water Authority of Jordan (WAJ). The well data was in Excel database format and contain local X, Y coordinates (Palestinian Grid) along with other hydrogeological, chemical, and isotopic data. The groundwater wells that contain complete chemical analyses in terms of major cations and anions and environmental isotopes were used in this study by integrating them into GIS as a point layer.

3-Geoprocessing: The Extract Function and mainly the clip command were used in order to extract the geology, structure, contour, and the well digital files, in order to fit within the Azraq basin. This is an essential step in GIS to create the new themes needed for spatial analysis. The advantage of this step is that it keeps the attributes of the newly created features in the output layer that is the same as those of the features in the layer being clipped. In addition, the output themes from the clipping operations are kept in the same coordinate system as the input layers.

4-Vector Conversion onto Raster: In order to perform the interpolation analysis, the study area converted from vector format into a grid format (raster). This step makes the analysis possible and restricts the interpolation surface to the boundary of the newly created grid. This is significant because the processing will only occur on the grid cells within the study.

Spatial Interpolation

A geostatistical module kriging was used to interpolate the point elevations of the Azraq basin. Spatial interpolation is simply defined as a process to estimate unknown values from points with known values. The models generate prediction surfaces and also uncertainty surfaces, giving an indication of how the predictions are made. In this study the unknown elevation values of the Azraq terrain at different locations were estimated through the kriging technique from known elevation points at various locations. The Geostatistical Analyst extension in ArcGIS is used for performing the analysis.

Geological & Hydrogeological Setting

According to the earlier geological investigations of the Azraq basin, a simplified geological map was created (Fig.2). Igneous and sedimentary rocks of different ages crop out in the basin and range in age from Maastrichtian to Pleistocene (Bender, 1974, Sahawneh, 1996). The sedimentary rocks consist mainly of limestone, chert, marl, clay and evaporites. The sedimentary rocks are of marine origin and consist of thick sediment up to 3.5 km. In the north and northeast, the basalt covers an area of about 11,000 km^2. Figure 2 shows the distribution of the outcropping rock formations in the basin. The basin is considered a depression and tectonically active and this is clearly seen from the various faults and lineament dominating in the area. The most important structure that affected the geology of the Azraq basin was the Sirhan-Fuluq Siwaqa fault system.

Along the geological formations that range between the Aptian of Lower Cretaceous to Pleistocene of Lower Quaternary, there are sets of water-bearing layers. The types of permeable formation layers, and the hydraulic relation between them, permit the classification of the Azraq basin into three main composite aquifers: Upper, Middle, and Deep.

The Deep Kurnub (K) aquifer (Aptian – Albian) consists mainly of a thick bed of coarse grained sandstone. The sandstone does not outcrop in the Azraq area and it is considered a confined aquifer. The two deep wells that were drilled and penetrated the K aquifer were used in this study. The AZ-1 and NDW-5 wells are both deep with a total depth of 1299 and 733 meters, respectively.

The Middle aquifer is locally called B2/A7 and it belongs to the Turonian – Campanion epoch. The aquifer consists mainly of limestone and dolomitic limestone with thin layers of chalk and evaporates, mainly gypsum. The aquifer is considered the most productive aquifer in the basin. It does not outcrop in the study area and it does demonstrate various thicknesses at different locations. The aquifer is considered confined throughout the basin, and it is recharged mainly from the Jebel (mountain) Druze recharge area in the north (BGR and WAJ, 1994).

The Upper aquifer is exposed in the entire basin and consists of four major water-bearing formations: The Rijam - B4 (Paleocene), The Shallala - B5 (Eocene), Basalt - Ba (Oligocene –Pleistocene) and the Quaternary Period deposits. The basalt extends from the center of the basin to the north and ends up in the highlands of Syria. 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, and the highest thickness of the basalt is estimated to be around 470 meters. The basalt aquifer is heavily exploited, since it is very productive and of good groundwater quality. The aquifer is under water table conditions and the water table is very deep in some locations, reaching up to 300 m. The B5 formation consists of chalk, chalky marl, marly limestone, and some sandy layers in some locations. The B4 formation consists of phosphatic and chalky marl, with a lens of black chert. The B4 aquifer receives recharge from precipitation and percolation from the upper basalt layer (BGR and WAJ, 1994). In the past, four springs used to exist and discharge from the B4 aquifer. The discharge ceased in 1990 due to the increase of pumping in the B4 formation. The Quaternary alluvial deposits are of great importance in the northeast of Azraq as they are considered a shallow aquifer. The aquifer is penetrated by many hand dug wells and is used for domestic and agricultural activities, or for salt production. The four permeable formations are hydraulically connected and are considered one aquifer unit that exists under water table conditions.

Digital Elevation Model

A digital elevation model (DEM) was created for the Azraq basin (Fig.3). The DEM consists of terrain elevations for ground positions in the basin. The elevation of the Azraq basin was obtained from CAD files containing the elevation values of the basin.

A geostatistical approach using the kriging method was used to construct the elevation model. The elevation model shows that the Azraq basin is an actual depression. The majority of the wells are located between 550 to 600 meters Above Sea Level (asl). The ground elevation increases as you move away from the depression. The highest elevation accurs in the north, and it is estimated to be around 1200 m asl.

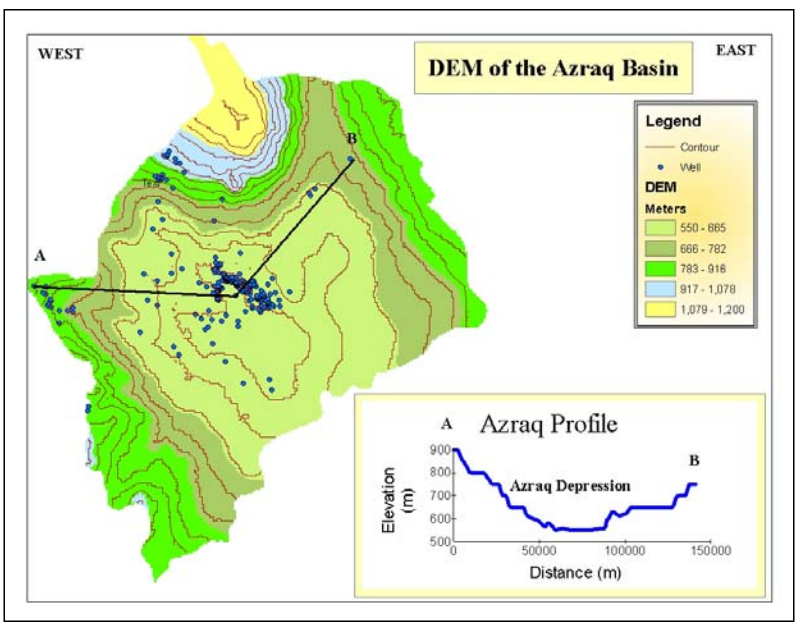

Fig. 3 DEM and Profile of the Azraq Basin

Results and Discussion

Groundwater Abstraction and Fluctuation in the Azraq Basin

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 Upper aquifer and the four springs in the basin between 1983 and 2003 is presented in (Table 1). The total groundwater abstraction almost tripled in 20 years. The abstraction has been increased from 21.57 MCM in 1983 to 59.3 MCM in 2003.

The table 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 flew to Jordan after the first Gulf war in 1990.

The amount of pumping exceeds the amount of recharge estimated by various authors (AGRAR & HYDROTECHNIC, 1977 and Barber et. al., 1973). This injudicious practice has caused the four major springs (Aura, Mustadhema, Qaisiyah, and Souda) to cease and dry out completely. In 1993 the natural discharge of the springs stopped entirely (Table1 and Fig.4).

Table 1 Total Abstraction from Groundwater and Springs

Year	Government Well	Springs	Private Wells	Total Discharge
	MCM	MCM	MCM	MCM
1983	9.50	10.57	1.50	21.57
1983	12.31	8.45	1.50	22.26
1984	14.36	7.27	2.00	23.63
1985	15.64	6.11	3.50	26.25
1986	13.72	3.57	4.50	21.79
1987	14.00	4.11	8.00	26.11
1988	22.35	2.15	12.00	36.50
1989	15.00	2.02	15.00	32.02
1993	13.00	0.00	30.20	43.20
1994	25.00	0.00	25.00	50.00
1995	24.12	0.00	26.50	50.62
1996	28.15	0.00	25.23	53.38
1997	26.83	0.00	26.86	53.69
1998	28.09	0.00	27.41	55.50
1999	27.20	0.00	29.25	56.45
2000	26.87	0.00	29.67	56.45
2001	26.46	0.00	31.31	57.77
2002	22.98	0.00	34.96	57.94
2003				59.3

These consequences caused the Ministry of Water and Irrigation to enforce new regulations by requesting that all owners of the groundwater private wells install a flow meter in order to calculate the amount of water abstraction. This step was necessary to manage and control the amount of abstraction, and observe the dynamic water level fluctuation. This approach presents more accurate and reliable database for evaluating the aquifer mass balance, and permits the prediction of any diverse effects from the over-pumping.
Table 1 shows that the amount of abstraction from the private and the governmental wells between 1994 and 2000 were almost identical. Nevertheless, a general trend of increased pumping was observed from the private wells. The abstraction increased around 54% from these wells between the period of 1996 and 2002, while the abstraction decreased 18% in the governmental wells for the same period.

There are very limited numbers of observation wells in the basin. The observation wells are mainly assigned to observe the water level of the Upper aquifer. Nevertheless, the observation wells are located in close proximity, which obscures the extent of the cone of depression and drawdown of the water level in the whole quifer. Azraq-12 is one of the wells that has a total depth of 116 meters and penetrates the B5/B4 water-bearing formations which is considered part of the Upper aquifer. The monitoring data for almost 18 years (Feb-86 to Dec-2004) are represented in (Fig. 5). The general trend indicates that the water level of the groundwater in the well has been declining with no evidence of replenishment.

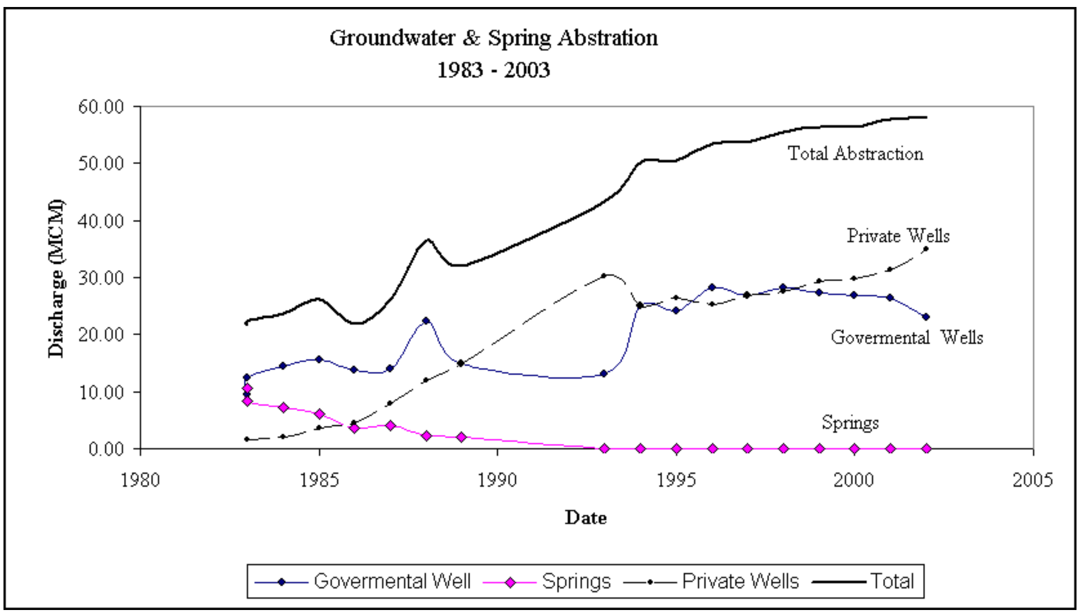

Fig.4 Groundwater and springs Abstractions between 1983-2003.

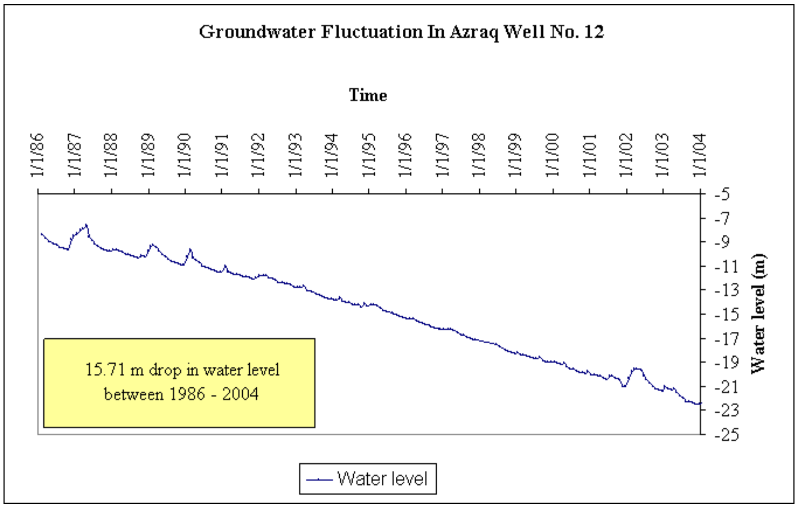

Fig. 5 Groundwater Fluctuation in Azraq – 12 Observation Well

Chemical and Environmental Isotopes Composition of precipitation

Chemical and isotopic analyses of precipitation were undertaken as a basis for investigating the origin and subsurface history of the groundwater in the Azraq Basin. The Azraq station was chosen to monitor the isotopic and chemical signature of the rain, so it could be used as a guideline to evaluate the groundwater recharge processes in the study area. The Azraq rainfall station is located at 533 m asl east to the Jordan Rift Valley (JRV). Figure 6 shows a cross section between the JRV passing the Ajloun Highlands and the Azraq Basin. Because of the limited amount of rain, the chemistry was restricted to the chloride concentration (Table 2).

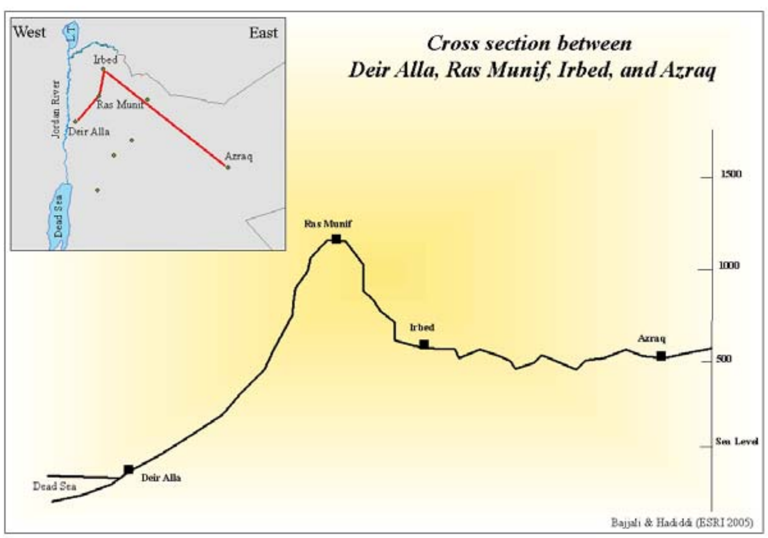

Fig. 6 Cross Section JRV - Ajloun Highlands - Azraq Basin

Table 2 Stable and Radioactive Isotope in Precipitation (Rain Samples > 10 mm)

Collection Date	δ ^{18}O ± 0.15	δ D ± 1.0	Tritium ± 1	Deuterium Excess	Rain amount (mm)	Chloride ppm
Feb-99	-1.72	3.7		17.5	12.6	
Jan-99	-3.13	-12.3	12.9	12.7	13	136.32
Nov-67	-1.77	7.4		21.6	13.2	26.27
Jan-90	-6.84	-40.2	NS.	14.5	15.6	
Oct-90	0.68	12.9	6.2	7.5	15.7	
Oct-67	-1.08	-11.5		-2.9	15.9	
Dec-87	-9.27	-52	13.4	22.2	17.9	
Jan-68	-9.77	-52.8		25.4	20.4	12.07
Mar-88	-3.6	-15	12.7	13.8	21.3	
Feb-90	-5.36	-20.9	NS.	22	22.7	
Jan-88	-6.86	-28.9		26	25.2	
Jan-98	-4.91	-25.2	6.9	14.1	27.2	
Mar-91	-5.36	-25.9	6.4	17	28.6	
Jan-89	-8.27	-45.4	9.4	20.8	32	
Jan-91	-7.66	-35.8	7.5	25.5	46.9	
Jan-05	-7.32	-39.6		19		

Due to the wide world variation in isotopic composition of precipitation (Dansgaard, 1964; Yurtsever and Gat 1981), the long-term Weighted Mean Value (WMV) was taken as the input function into a hydrological system. The available isotope data from the rainfall station from 1988 to 1999 was employed to provide averages based on monthly composite precipitation samples.

Chemical Composition of Precipitation

Chemical analyses of the precipitation in Jordan demonstrate a wide range of salinity between 25 to 140 ppm (Bajjali, 1990). This concentration is considered high for precipitation attributed to dust and proximity to major saline-water bodies (Bajjali, 2004). Due to the low amount of rain, only the Cl^- parameter was analyzed at different times (Table 2). The Cl^- concentration was widely variable, 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. Due to the lack of major cations and anions, it will be difficult to attribute the high chloride to salt aerosols. The Dead Sea or the Mediterranean Sea is relatively distant. Nevertheless a salt mine does exist in the Azraq Basin. Salt aerosol originating from the mine location is a possibility, and that depends greatly on wind velocity and directions.

Isotopic composition of precipitation

The general relationship between $\delta^{18}O$ and δD for natural waters in the Eastern Mediterranean was found to be linear, and represented by a line called Eastern Meteoric Water Line (EMWL). The relationship can be expressed by the following equation (Gat and Carmi 1970).

$$\delta D = 8\delta^{18}O + 22\ (‰)$$

The deviation from the (EMWL) is called Local Meteoric Water Line (LMWL) and can be expressed through the deuterium excess parameter (d). The d-parameter is defined as $d = \delta D - 8*\delta^{18}O$ (Dansgaard, 1964). The location of the data on the LMWL indicates the origin of the air moisture.

The relationship between the $\delta^{18}O$ and δD of the Azraq rainfall station precipitation are shown in (Fig. 7).

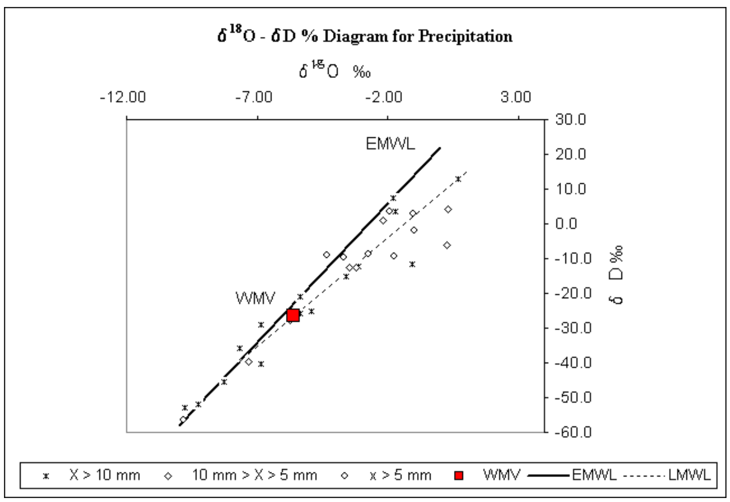

Fig. 7 Oxygen-18 - Deuterium Diagram of the Precipitation in Azraq

The regression line for the $\delta^{18}O$ and δD was calculated to be:

$$\delta D = (6.29 \pm 0.48)\ \delta^{18}O + (8.63.07 \pm 2.84) \quad n= 15$$

The correlation coefficient was found to be high ($R^2 = 0.92$). The ± in the equation indicates 95 % confidence interval on the slope and the intercept. Figure 7 shows that the monthly samples at all the stations fall very close to the LMWL. The most divergent values relative to EMWL in Figure 7, usually enriched in both oxygen-18 and deuterium, are those of months with deficient rainfall (March-89, April-88, and May-88).

Tritium Concentration in Precipitation:

A high tritium concentration in the precipitation will be used as an indicator for the groundwater recharge. If a shallow groundwater aquifer in the Azraq basin is found to be tritiated, it will be most probable that the rain infiltrated down to the aquifer.

In Jordan, large variations in tritium occurred during the period from 1987 to 1991 (Bajjali, 1990). The monthly tritium concentration in the Azraq Basin also demonstrates the variability between December 1987 and January 1999 (Table 2). In general, tritium data show that there is a general trend of decreasing tritium concentrations over time. Nevertheless, tritium content on January 1999 is higher than the values of March 1988 to February 1998. This could be attributed to specific air moisture entering the area at that time with high tritium content.

The weighted average of tritium concentration in the atmosphere from Azraq rainfall station for the winter season of 1987/1999 was approximately 8.8 TU. This value can be used to characterize the input function between local rains and recharge events.

Chemical Classification of groundwater

The chemical composition of groundwater is indicative of its origin, transit time in the water-bearing formations, and other factors. Total Dissolved Solid (TDS) values of the groundwater wells tapping the different aquifers demonstrate wide ranges in concentration. The lowest TDS was 53 mg/l recorded for the deep sandstone aquifer, and the highest was 2729 mg/l recorded for the Upper aquifer. The compositions of the water (by equivalent) vary considerably. The chemical composition of all the samples (Appendix 1) were plotted in the Piper diagram (Fig. 8), which showed differences for the ionic composition of groundwater tapping the three aquifer systems.

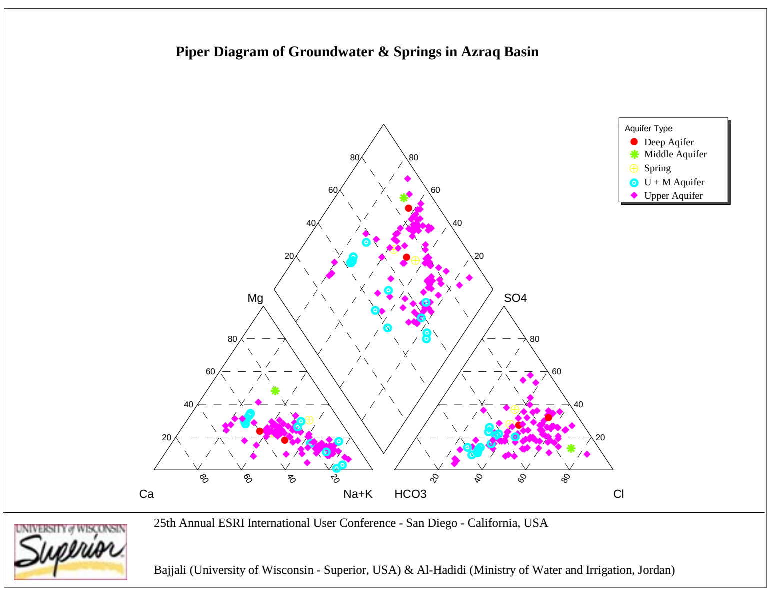

Fig. 8 Groundwater Classification in the Azraq basin

The groundwater demonstrates chemical composition as alkaline earth water with an increased portion of alkalies with prevailing chloride. The groundwater wells are also classified mainly into three major types: (1) sodium chloride, (2) calcium carbonate, and (3) no water dominant. The first and third types are the most dominant. Many wells that are tapping the Upper aquifer have similar chemical composition, and are classified as no dominant type of water, are not geographically near each other, can be considered from mixed sources. The NaCl type of water is dominated by dissolution of evaporite minerals, such as halite and sylvite found within the lithology, from where the groundwater flows. Other sources could be from evaporation effects. The water that is used for irrigation will become subject to evaporation leaving the various types of salts to precipitate on the ground.

The continuous irrigation process will continue to precipitate and dissolve the salt that will eventually build up in the shallow strata of the Upper aquifer. This is very well demonstrated in some private shallow wells, where the salinity was recorded to be above 1,000 mg/l and its type of water was mainly NaCl with few exceptions. Very few samples that demonstrate high HCO_3^- concentrations and low of Na^+, Cl^-, and $SO4_2^-$ concentrations are classified as calcium bicarbonate type of water. This groundwater belongs to shallow, hand-dug wells and represents relatively very young groundwater.

Classification of groundwater based on Environmental isotopes

The stable isotope data of the groundwater wells tapping the various aquifers, in conjunction with the WMV of Azraq and Ras Munif precipitation, were plotted on the $\delta^{18}O$ - δD diagram (Fig. 9). Ras Munif rainfall station is located in Yarmouk Basin at an elevation of 1150 meter asl and has WMV of -7.1 ‰ and – 33 ‰ for $\delta^{18}O$ and δD respectively (Bajjali, 2004). The graph shows that the groundwater samples revealed a wide variation in $\delta^{18}O$ and δD content. With a close look at the isotopic data, one can observe that there is at least 1.9 ‰ and 11.2 ‰ in $\delta^{18}O$ and δD, respectively. The groundwater samples are positioned broadly between the EMWL and Global Meteoric Water Line (GMWL).

The groundwater samples can be divided into three distinct groups.

1. The first group contains mainly the Upper aquifer with few samples from the Middle aquifer.
2. The second group contains the Middle aquifer and the deep Azraq well that penetrates the three aquifer systems.
3. The third group contains the Deep aquifer that penetrates the sandstone aquifer.

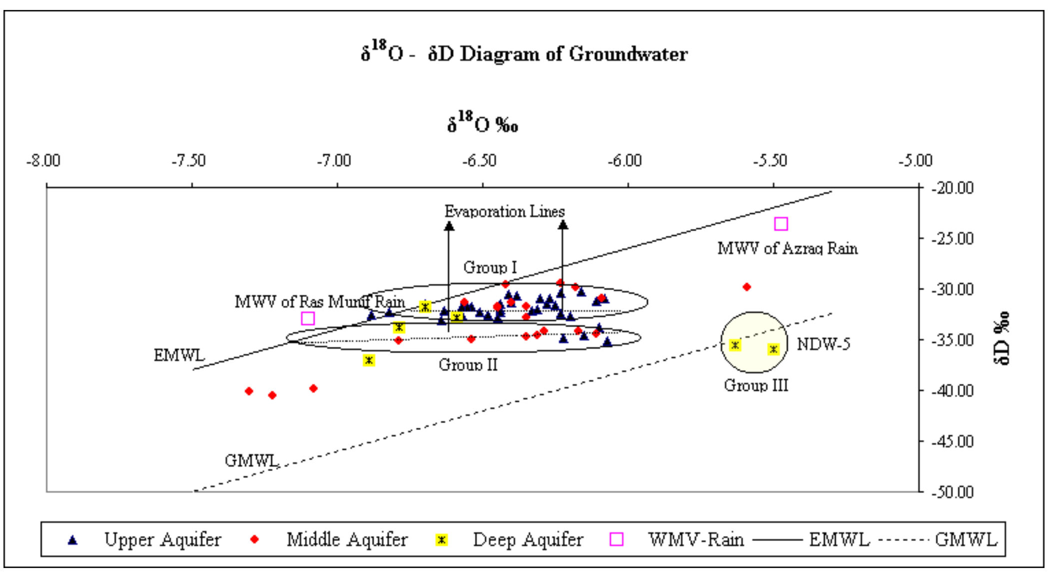

Fig. 9 $\delta^{18}O$ and δD Diagram of the Azraq Groundwater and Precipitation

Without exception, all the groundwater of the three aquifer systems is more depleted than the WMV of precipitation in Azraq Basin and is located farther away from it. This is a substantial indication that the groundwater can not be recharged locally from rain originating from altitudes similar to the Azraq rainfall station, which is 533 m asl. 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.

The location of the various groundwater samples on the $\delta^{18}O$ - δD diagram shows that the recharge elevation area of the Azraq Basin is varied. This means that the rain infiltration to the groundwater of various aquifers took place at different altitudes.

The first group clusters along an evaporation line and originates from the EMWL. The isotopic data are scattered widely along the evaporation line, which indicates that the infiltrated water down-gradient is subject to different degrees of evaporation before infiltration. Some of the groundwater wells tapping the Upper aquifer are used extensively for irrigation year round. This practice will make the groundwater that has been used for agriculture become enriched with the isotopic composition due to direct evaporation. This access water will eventually return back to the aquifer with the signature of the evaporation effects. It is also possible that the variation of the isotopic composition of the groundwater could be due to the stratification of the groundwater (Bajjali, 1994). 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. In addition, the heavy pumping in summer would cause greater mixing of the water from the different water-bearing formations. The first group also includes a few wells that tap the Middle aquifer. This is the B2/A7 aquifer that has a hydraulic relationship with the basalt of the Upper aquifer in certain locations of the basin. So the isotopic composition of these wells could be mixing between the two types of water.

The second group consists of the Middle aquifer, which is also scattered along an evaporation line originating from a point at the EMWL. The origin of the evaporation line is much more depleted than the origin of the evaporation line of the first group that contains the Upper aquifer. This indicates that the recharge of the Middle aquifer originates from a higher elevation area than the recharge area of the Upper aquifer. The location of the samples of the Middle aquifer on the $\delta^{18}O$ - δD diagram is more depleted than the WMV of Ras Munif rain. This means that the recharge elevation for the Middle aquifer should come from elevation area higher than 1150 meter asl. The DEM (Fig. 3) shows that such elevation is identical to the highest altitude in the northern territory of the basin along the Syrian border.

Furthermore, the scattering samples along an evaporation line could simply mean that the water is subject to evaporation before infiltration. The isotopic composition of the water from the deepest well (AZ-1) of the Deep aquifer is also found within this group. 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-7 (Middle aquifer) and KM 134 (Upper aquifer) wells were sampled at different times for isotopic composition between May 1993 and January 1993, respectively (Appendix 1). The data of the two wells were plotted on the $\delta^{18}O$ - δD diagram (Fig. 10). Both water samples demonstrated a very wide range of $\delta^{18}O$ and δD, and this can only be attributed to evaporation before infiltration.

The third group is located in the GMWL, which signifies a recharge origin other than the climate that currently dominates Jordan. NDW-5 well that penetrates the Deep sandstone aquifer did not reflect the isotopic composition of the precipitation in Jordan. The samples were characterized by the depleted isotopic signature typical of late Pleistocene (Lloyd, 1980; Bajjali et. al. 1997, Bajjali and Abu-Jaber, 2001)

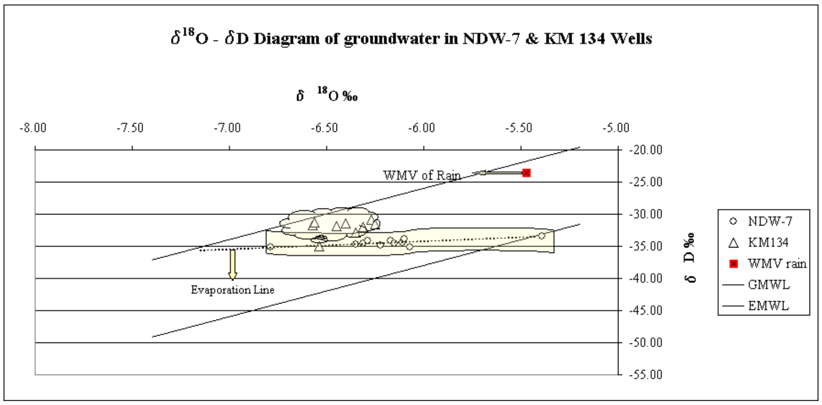

Fig. 9 $\delta^{18}O$ and δD Diagram of NDW-7 & KM 134 Groundwater Wells

Radioactive Tritium in Groundwater

The groundwater in the Azraq Basin demonstrates that there is no tritium or a very low concentration or less than 1.6 T.U. This simply indicates that the recharge took place before 1952. Nevertheless, the WAJ files indicate that some hand-dug wells that penetrate the alluvium have a reasonable concentration of tritium above the analytical error of the lab instruments. This is very well observed in the alluvium aquifer in different part of the north-east desert of Jordan (Bajjali, 1997).

The tritium data show that the travel time of the Upper aquifer exceeds 40 years. The travel time of the groundwater of the Upper aquifer was estimated using radioactive carbon -14 technique (Al-Momani, 1996). The age of water was obtained for two wells and estimated to vary between 11,000 to 14,500 years. The high residence-time values of the groundwater are simply an absolute dating procedure without any carbon-14 correction. The Upper aquifer consists of basalt and carbonate materials and the corrections are essential in dating the groundwater with carbonate matrix (Clark and Fritz, 1997).

Summary

The abstraction of the groundwater in the Azraq basin has increased on a yearly basis and went beyond the safe yield. The groundwater pumping almost tripled between the period of 1983 and 2003, where the abstraction increased from 21.57 MCM to 59.3 MCM, respectively. This performance lowered the water table of the Upper aquifer in some areas dramatically, in some wells the water level declined up to 20 meters. The consequences negatively affected the water balance and the hydrogeological conditions of the area. The over-pumping caused the major four springs discharge, originating from the Upper aquifer, to dry out in the Azraq oasis.

The salinity of the precipitation in the basin demonstrates relatively high salinity and is attributed to the dust and the proximity from major saline-water bodies.

The isotopic composition of the groundwater divided the groundwater into three distinctive groups. The first two groups are associated with the EMWL, and the third group associated with the GMWL. The recharge area of the groundwater of the Upper and Middle aquifers is much higher than the average elevation terrain of the Azraq basin. Furthermore, the Middle aquifer of the B2/A7 has a recharge elevation area higher than the recharge elevation area of the Upper aquifer.

The recharge period of the first two aquifer systems is associated with the recent climate that dominates Jordan today. The groundwater of the Deep Kurnub sandstone aquifer is classified as paleowater and recharged during the Pleistocene Epoch.

The groundwater is classified as alkaline earth water with a prevailing chloride concentration.

References:

AGRAR UND HYDROTECHNIC Gmb H & BUNDESANSTALT FUR GEOWISSENSCHAFIEN UND ROHSTOFFE (1977). National Water Master Plan for Jordan, Volumes I to VII. Hanover and NRA- Jordan

Al-Hadidi, K. and Subuh A., (2001). Jordan Badia Research and Development Program: Integrated Studies of Azraq basin for Optimum Utilization of the Natural Resources, Water Group,. Vol. 4. The higher Council of Science and Technology, Amman- Jordan

Al-Momani, M., (1996). Isotope Field Application for Groundwater Studies in the Middle East, IAEA-TECDOC-890. IAEA, Vienna.

Bajjali, W., (2004) Recharge mechanism and hydrochemistry evaluation of groundwater in the Nuaimeh area, Jordan, using environmental isotope techniques. Hydrogeology Journal 10.1007/s10040-004-0352-2, April 2004.

Bajjali, W., and Abu-Jaber, N., (2001). Climatological signals of the paleogroundwater in Jordan. Journal of Hydrology, vol.243 (1-2), pp. 133 – 147.

Bajjali, W., Clark, I. and Fritz, P., (1997). The artesian thermal groundwaters of northen Jordan: insights into their recharge history and age. J. Hydrol. 192: 355-382.

Bajjali, W., (1997). Using ArcView to determine the origin of groundwater salinity in Dhuleil, Halabat, and Samra area of Jordan. ESRI User Conference, San Diego, Ca, USA, July 7-11.

Bajjali, W. (1994). Recharge and regional circulation of thermal groundwater in northern Jordan using isotope geochemistry. Ph.D Thesis, University of Ottawa, Canada. Pp.257

Bajjali, W., (1990). Isotopic and Hydrochemical Characteristics of Precipitation in Jordan, M.Sc. Thesis, Jordan University. Amman-Jordan. pp.99.

Barber, W., Carr, D. P. Raikes & Partners, (1973). Digital Model of Shallow Aquifer Complex of the Azraq Basin. East Jordan. Consultant's Report. Development and Use of the Groundwater Resources of Eastern Jordan. FAO/ SEJOR /71/525

Bender, F., (1974). Geology of Jordan. Gebruder Borntraeger. Berlin. Stuttgart. pp.196.

BGR and WAJ., (1994). *Groundwater Resources of Northern Jordan*. Vol. 3– Structural Features of the Main Hydrogeological Units in Northern Jordan. Unpubl. Rep. Water Authority of Jordan (WAJ), Fed. Inst. for Geosc. and Nat. Res. (BGR), BGR-Archive No. 112708, Amman, Jordan.

Clark, I. D. and Fritz, P., (1997). Environmental Isotopes in Hydrogeology. CRC Press, pp. 352.

Dansgaard, W., (1964). Stable isotope in precipitation. Tellus, 216: 436-468.

Gat, J.R., and Carmi, L., (1970). Evolution of the isotopic composition of atmospheric waters in the Mediterranean Sea area. J. Geophys. Res., 75: 3039-3048.

HCST, (1999). Integrated Studies of Azraq Basin for Optimum Utilization of the Natural Resources. Internal Report, HCST, Amman, Jordan

Lloyd, J.W., (1980). Aspects of environmental isotope chemistry of groundwaters in eastern Jordan. In: Arid Zone Hydrology: Investigations with Isotope techniques. Proceeding AG-158, International Atomic Energy Agency, Vienna.

Sahawneh, J., (1996) Geology of Al Azraq Basin, Geology Directorate, Subsurface Geology Division, Groundwater Basin Project. Internal Report No. 2, Natural Resources Authority. Amman Jordan

Yurtsever, Y. and Gat, J.R. (1981). Atmospheric Waters. Stable Isotopes Hydrology, Deuterium and Oxygen-18 in the water cycle. Technical Reports Series No. 210. IAEA, Vienna.

United Nations Development Program (UNDP) (1966). General Report On The Ground-Water Investigation of the Azraq Basin. United Nations, New York.

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

CODE	Tritium	δ ^{18}O	δ D	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-
	TU±1	± 0.15	± 1	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*
Upper Aquifer												
F 1028	-	-6.23	-32.40	693.8	37.7	18.9	159.9	9.8	158.6	54.2	246.4	8.4
F 1037	0.2	-6.48	-32.50	466.4	16.4	10.7	113.9	7.4	133.6	56.2	118.6	9.7
F 1038	0.0	-6.54	-31.70	377.2	30.6	2.9	81.9	5.5	126.3	42.2	74.2	13.6
F 1039	0.0	-6.30	-30.90	663.3	32.7	20.9	158.7	12.9	114.7	69.1	246.4	7.9
F 1040	-	-6.70	-31.50	533.3	22.9	14.0	124.0	12.9	133.0	73.9	143.1	9.6
F 1029	-	-6.33	-32.20	435.7	18.4	10.9	102.4	6.7	137.3	49.0	101.5	9.6
F 1030	-	-6.44	-32.00	508.8	31.4	12.2	116.8	7.4	126.3	47.0	156.9	10.7
F 1031	0.3	-6.44	-32.30	146.5	0.0	0.0	67.2	6.3	0.0	0.0	68.9	4.3
F 1033	0.0	-6.63	-32.20	284.6	28.6	4.6	49.5	4.3	128.1	24.5	36.6	8.5
F 1034	-	-6.51	-32.30	424.5	14.8	9.2	105.6	7.0	126.9	55.2	94.4	11.3
F 1035	-	-6.28	-31.50	339.3	20.0	10.5	68.3	5.1	120.2	39.4	62.5	13.5
F1036	0.0	-6.45	-32.90	-	-	-	-	-	-	-	-	-
F 1053	0.6	-6.91	-35.40	1004.3	93.4	32.8	163.1	18.4	272.1	194.9	229.0	0.7
F 1022	0.1	-6.11	-31.20	352.7	14.6	6.7	82.8	6.7	115.9	48.5	70.3	7.3
	0.0	-6.09	-31.00									0.0
F 1021	0.0	-6.55	-31.80	1313.0	43.9	22.0	438.4	30.9	158.6	234.7	384.5	0.0
F 1062	0.0	-6.08	-31.00	291.0	11.8	6.9	74.1	0.0	100.7	32.6	55.0	9.9
F 1091	0.0	-6.57	-32.50	309.5	12.8	7.3	70.8	0.0	128.7	26.9	58.9	4.0
F 1054	0.1	-6.44	-31.50	437.6	21.0	10.9	99.4	7.4	115.3	57.6	119.6	6.3
				2729.1	253.9	127.0	420.0	43.8	442.3	733.0	707.2	2.1
F 1058	0.0	-6.40	-31.30	-	-	-	-	-	-	-	-	-
F 1059	0.7	-6.20	-32.70	552.2	26.3	15.2	129.4	8.6	125.7	68.2	166.9	12.1
F 1060	0.0	-6.41	-30.60	392.2	11.8	7.8	103.0	0.0	124.4	36.0	106.2	3.0
F 1312	0.0	-6.38	-30.70	233.4	14.0	10.5	36.8	5.1	109.8	13.0	32.7	11.6
F 1310	0.0	-6.23	-30.40	264.2	14.0	14.0	43.7	5.5	102.5	26.4	45.1	13.0
F 1310	0.0	-6.16	-30.30	264.2	14.0	14.0	43.7	5.5	102.5	26.4	45.1	13.0
F 3946	0.2	-6.88	-32.60	-	-	-	-	-	-	-	-	-
F 3946	0.0	-6.82	-32.30	-	-	-	-	-	-	-	-	-
F 1305	1.6	-6.31	-32.00	345.4	15.8	6.8	80.7	7.8	101.3	46.1	76.7	10.2
F 1305	0.0	-6.27	-30.90	345.4	15.8	6.8	80.7	7.8	101.3	46.1	76.7	10.2
F 1305	0.4	-6.57	-31.70	345.4	15.8	6.8	80.7	7.8	101.3	46.1	76.7	10.2
F 1305	0.0	-6.25	-31.60	345.4	15.8	6.8	80.7	7.8	101.3	46.1	76.7	10.2
F 1350	0.0	-6.15	-34.60	379.5	10.8	14.2	171.0	5.0	-	-	175.0	3.5
F 1350	0.0	-6.22	-34.80	379.5	10.8	14.2	171.0	5.0	-	-	175.0	3.5
F 1350	-	-6.07	-35.20	379.5	10.8	14.2	171.0	5.0	-	-	175.0	3.5
F 1350	-	-5.39	-33.40	379.5	10.8	14.2	171.0	5.0	-	-	175.0	3.5
F 1350	0.0	-6.10	-33.80	379.5	10.8	14.2	171.0	5.0	-	-	175.0	3.5

Middle Aquifer												
CODE	Tritium	$\delta\ ^{18}O$	δ D	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	NO_3^{-}
	TU±1	± 0.15	± 1	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
F 1123	0.0	-6.23	-29.40	289.6	18.6	15.0	45.1	7.4	105.5	17.3	66.7	13.9
F 1124	0.0	-5.59	-29.80	-	-	-	-	-	-	-	-	-
F 1125	0.0	-6.42	-29.60	269.6	12.2	0.5	69.7	5.9	92.1	35.0	44.4	9.8
F 1312	0.8	-6.18	-29.90	233.4	14.0	10.5	36.8	5.1	109.8	13.0	32.7	11.6
F 1305	-	-6.40	-31.40	345.4	15.8	6.8	80.7	7.8	101.3	46.1	76.7	10.2
F 1125	0.2	-6.56	-31.30	269.6	12.2	0.5	69.7	5.9	92.1	35.0	44.4	9.8
F 1125	0.6	-6.45	-31.90	269.6	12.2	0.5	69.7	5.9	92.1	35.0	44.4	9.8
F 1125	-	-6.54	-35.00	269.6	12.2	0.5	69.7	5.9	92.1	35.0	44.4	9.8
F 1125	-	-6.35	-32.90	269.6	12.2	0.5	69.7	5.9	92.1	35.0	44.4	9.8
F 1360		-7.30	-40.20	67.3	7.4	10.4	12.5	0.4	5.5	4.4	18.3	8.5
F 1360	0.0	-7.08	-39.90	67.3	7.4	10.4	12.5	0.4	5.5	4.4	18.3	8.5
F 1360	-	-7.22	-40.50	67.3	7.4	10.4	12.5	0.4	5.5	4.4	18.3	8.5
F 1358	-	-6.35	-31.70	13.7	0.6	0.6	1.8	0.1	-	-	0.9	9.7
F 1358	-	-6.09	-31.00	13.7	0.6	0.6	1.8	0.1	-	-	0.9	9.7
F 1358	-	-6.45	-31.80	13.7	0.6	0.6	1.8	0.1	-	-	0.9	9.7
F 1350	0.0	-6.31	-34.60	379.5	10.8	14.2	171.0	5.0	-	-	175.0	3.5
F 1350	0.0	-6.35	-34.70	379.5	10.8	14.2	171.0	5.0	-	-	175.0	3.5
F 1350	0.0	-6.17	-34.20	379.5	10.8	14.2	171.0	5.0	-	-	175.0	3.5
F 1350	0.0	-6.29	-34.20	379.5	10.8	14.2	171.0	5.0	-	-	175.0	3.5
F 1350	0.0	-6.79	-35.20	379.5	10.8	14.2	171.0	5.0	-	-	175.0	3.5
F 1350	-	-6.11	-34.40	379.5	10.8	14.2	171.0	5.0	-	-	175.0	3.5
Deep Aquifer												
F 1053	-	-6.89	-37.00	1004.3	93.4	32.8	163.1	18.4	272.1	194.9	229.0	0.7
F 1053	0.0	-6.79	-33.80	1004.3	93.4	32.8	163.1	18.4	272.1	194.9	229.0	0.7
F 1053	0.0	-6.70	-31.70	1004.3	93.4	32.8	163.1	18.4	272.1	194.9	229.0	0.7
F 1354	0.0	-5.50	-35.90	1197	156.3	34	128.3	17.1	228.8	322.7	301.4	-
F 1354	0.0	-5.63	-35.60									