DEVELOPING RENEWABLE GROUND WATER RESOURCES IN ARID LANDS

PILOT CASE: THE EASTERN DESERTOF EGYPT

EASTERN DESERT PROJECT

GEOCHEMICAL AND ISOTOPIC CONSTRAINTS ON THE ORIGIN OF THE EASTERN DESERT GROUNDWATERS

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Geochemical and Isotopic Constraints on the Origin of the Eastern Desert Groundwaters: A Progress Report

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Executive Summary

Chemical and isotopic compositions of groundwater samples from the Eastern Desert are being analyzed in a project supported by the U.N. Development Program and the Global Environmental Facility International Water Fund. Most samples have been collected from production and observation wells and open wells in wadis adjacent to the Nile Valley, and some from within the Precambrian terrane of the central Eastern Desert. Preliminary analysis of the data indicate that two end-member water compositions can be identified from stable isotope compositions: (1) isotopically enriched water, most likely recharged recently by flash-floods, such as the water in shallow aquifers sampled at Wadi El Tarfa, Arab El Ashrafia, and in the Precambrian terrane of the Red Sea Hills, and (2) isotopically depleted water, most likely Pleistocene water from the Nubian sandstone aquifer. Waters sampled in the southwestern part of the study area (west of the Red Sea Hills) are dominated by the Nubian aquifer contribution. The isotopic composition of the Nubian aquifer waters in the Eastern Desert appears to be distinct from that in the Western Desert oasis areas. Where the Nubian Aquifer is present beneath alluvial deposits, either pure Nubian aquifer paleowater or mixed Nubian/recent waters are likely to be produced in high yield. Within the Precambrian terrane of the Red Sea Hills, recent runoff from impermeable basement rocks is concentrated in wadis and may recharge reservoirs in thick alluvial deposits or highly fractured rock in shear zones. Further study is needed to evaluate the extent and recharge rate of groundwater reservoirs within the Nubian aquifer and Red Sea Hills in the Eastern Desert. Ongoing chemical and isotopic studies may provide critical constraints on these questions.

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Introduction

Groundwater in arid regions is an especially valuable resource. Understanding the origin and magnitude of groundwater is crucial for optimal water resource management. In the Eastern Desert of Egypt, groundwater resources are being used increasingly for agricultural development. Much of this development is occurring in wadis that flow into the Nile Valley. Much can be learned about the origin and age of groundwater by analyzing its chemical and isotopic composition. A new program of chemical and isotopic analysis of groundwater in the Eastern Desert began in 2003 with the support of the United Nations Development Program. This paper summarizes stable isotope results and gives a preliminary analysis of geochemical data obtained to date. A synthesis of the data is presented in terms of the origins of the Eastern Desert waters in relation to their geographical occurrence.

Methods

Field methods

Two 500-mL samples were collected at each location in polyethylene bottles for chemical and isotopic analyses of groundwater. One of these samples was filtered with 0.45µm polypropylene syringe filters in the field. Temperature and pH were measured in the field. Sample location was recorded with hand-held GPS receiver.

Laboratory methods

Anion concentrations and alkalinity were measured at the Aqueous Geochemistry Laboratory (AGL), University of Illinois at Chicago (UIC). Total alkalinity was measured by titration on a Mettler DL70 ES Titrator using 0.100M HCl. Anions were analyzed by ion chromatography on a Dionex DX-100 fitted with an AG-10 column and an ASRS-I suppressor. The eluent was 0.1 M NaOH. Peak Simple calculated the eluted peaks and integrated the areas, which were used for the construction of calibration curves and determination of ionic concentrations in samples. At least 5 standards spanning an order of magnitude (1-10 ppm) were used to construct the calibration curves for F^-, Cl^-, SO_4^{2-}, Br^-, and NO_3^-. Samples were filtered with a 0.45 µm polypropylene filter, diluted with 18.2 MΩ water if their concentrations exceeded the calibration curve, and stored in polyethylene bottles leached with ~2M HNO_3. 1 mL of sample was injected at least three separate times and values were averaged with experimental error <2%.

Cations were analyzed by inductively-coupled plasma atomic emission spectrometry at Argonne National Laboratory and the University of Illinois at Chicago. Stable isotope ratios of hydrogen and oxygen in water samples were measured by the CO_2 equilibration (Socki et al., 1992) and zinc reduction (Coleman et al., 1982) methods, respectively.

Stable Cl isotope ratios were measured by first converting the Cl^- to CH_3Cl at the AGL. The amount of sample yielding ~3 mg Cl^- was measured and gently heated to reduce to 10 mL if necessary. Two mL of a buffer composed of 0.004 M Na_2HPO_4 and 0.107 M citric acid were added along with 4 mL of 1 M KNO_3. Cl^- was precipitated with excess 0.38 M $AgNO_3$ (3 mL). The AgCl was transferred to 45-mL centrifuge tubes and centrifuged in a IEC Centra CL2 at 3800 rpm for 8 minutes. The supernatant was removed and 40 mL of dilute HNO_3 was added. The samples were centrifuged as above, the supernatant was removed, and the AgCl precipitate was subsequently washed with 20, 15, and 10 mL of dilute HNO_3 in the same manner. The samples were transferred into glass tubes that had been baked in a 550 °C oven for 2 hours and were dried in a 60 °C oven. At the Environmental Isotope Geochemistry Lab (EIGL) at UIC, each tube was attached to a vacuum line, evacuated, and 35 μM of CH_3I was cryogenically transferred into the tube. The tube was sealed and placed in a 300 °C oven for 2 hours. The resulting CH_3Cl was purified by cryogenic distillation on a vacuum line using dry ice/acetone and pentane/liquid nitrogen solutions to regulate temperature, and sealed in another evacuated glass tube. The CH_3Cl was then analyzed for stable Cl isotopes on either a ThermoFinnigan DELTAplusXL or VG Prism II mass spectrometer. This method is based on published methods of Eggenkamp (1994) and Holt et al. (1997).

^{36}Cl was measured by Accelerator Mass Spectrometry (AMS) at the PRIME Laboratory at Purdue University. Samples were prepared for AMS analysis by the precipitation and purification of AgCl from groundwater samples at UIC. A 5 cm bed of 1-X8 anion exchange resin was placed in each ion exchange chromatographic column (1 cm x 25 cm). The resin was conditioned with 150 mL 1.5 M HNO_3. The complete removal of Cl from the resin was determined by the addition of 3 drops 1 M $AgNO_3$ to the last 5 mL of eluant. The columns were then washed with 300 mL of 18.2 MΩ water. The samples were measured and placed in the column. This was followed by 10 mL of 0.1 M NH_4OH, 10 mL 0.05 M HNO_3 and 5 mL 0.15 M HNO_3. The subsequent 17 mL of 0.15 M HNO_3 was collected in a 45 mL centrifuge tube containing 3 drops of 1 M $AgNO_3$. Three more drops of 1 M $AgNO_3$ and 5 drops of low chloride, concentrated HNO_3 were added to centrifuge tube. The tube was shaken and refrigerated overnight. The columns were conditioned and washed with 150 mL 1.5 M HNO_3 and 300 mL of 18.2 MΩ water as described above. The tubes were centrifuged in an IEC Centra CL2 at 4000 rpm for 20 minutes. The supernatant was removed and 5 mL of 18.2 MΩ water, 20 drops of low chloride, concentrated NH_4OH were added to each sample. The AgCl was agitated until dissolved and placed on the resin bed. The same sequence of eluant solutions and collection technique as described above was used to purify the Cl. After overnight refrigeration the samples were centrifuged as described above and washed with ~1 mL of 18.2 MΩ water. Another ~1 mL of 18.2 MΩ water was added and the sample was transferred to a tared, labeled micro centrifuge tube with a disposable pipet. The samples were centrifuged in an International Equipment Company MediSpin model 120 centrifuge for 30 minutes. The supernatant was removed and the micro centrifuge tubes placed in a 60 °C oven until dry. The capped samples were weighed and sent to the PRIME lab.

Sample Locations

The Eastern Desert of Egypt extends from the Nile River to the Red Sea, covering an area more than 200,000 km^2. In the central part of the Eastern Desert is a mountain range cored by Precambrian basement (550-900 Ma), with prominent peaks formed by granite bodies, and volcano-sedimentary rock units. The mountains are drained by a series of wadis into the Nile River on the west and the Red Sea on the east. The modern Nile River valley was excavated and developed as a subsequent stream to the numerous valleys emanating from the elevated Red Sea hills to the east (Said, 1993). Most groundwater is hosted either in shallow alluvial aquifers, Eocene Limestone, Nubian Sandstone Aquifer, or fractured basement aquifer.

Figure 1 shows the locations of the samples collected and analyzed to date with the exception of those from the Precambrian areas of the Red Sea Hills in the central Eastern Desert (Sheikh El Shazly, Bir Um Ghanam, Hafafit, and Fawakhir). Most of the samples are from areas adjacent to the Nile Valley, between latitudes 26°00’ and 29°27’ N, and longitudes 31°16’ and 33°09’ E, while one set of samples was collected from Wadi Darrah near the Red Sea near 27°59’ N latitude and 33°13’ E longitude.

Stable Isotope Ratios of Hydrogen and Oxygen

The stable isotope ratios of hydrogen and oxygen are shown in Table 1 and Figure 2, which includes data for samples from the present study as well as: Nubian Aquifer paleowaters from the Western Desert (Sturchio et al., 2004); Gulf of Suez area paleowaters, also from the Nubian Aquifer (Sturchio et al., 1996); shallow aquifers in the Wadi Tarfa area (Sultan et al., 2000); and data for modern precipitation from Sidi Barrani (IAEA/WMO, 1998).

Stable isotope ratios are reported in "delta" notation, defined as:

$$\delta D = \left[\frac{\left(\frac{D}{{}^{2}H} \right)_{sample}}{\left(\frac{D}{{}^{2}H} \right)_{standard,VSMOW}} - 1 \right] \times 1000$$

$$\delta^{18}O = \left[\frac{\left(\frac{{}^{18}O}{{}^{16}O} \right)_{sample}}{\left(\frac{{}^{18}O}{{}^{16}O} \right)_{standard,VSMOW}} - 1 \right] \times 1000$$

The Eastern Desert groundwater samples have a wide range in hydrogen and oxygen isotope ratios, from a relatively depleted composition of $\delta D = -59.2$, $\delta^{18}O = -7.9$ in Bir Laquiba to a relatively enriched composition of $\delta D = +32$, $\delta^{18}O = +5.2$ at Wadi El Sheikh Fadl. A previous study by Sultan et al. (2000) showed that the groundwaters of the Wadi Tarfa area are mostly evaporated flash flood waters, with relatively short underground residence times indicated by the presence of live tritium (i.e., <45 years). The most enriched sample, from Wadi Sheikh El Fadl, was shown by Sultan et al. (2000) to be evaporated Nile River water. Apart from seven sample locations (two in Wadi Matuly, one in Arab El Ashrafia, and four in the Precambrian terrane of the central Eastern Desert at Sheikh El Shazly, Bir Um Ghanam, Hafafit, and Fawakhir) that have isotopic characteristics similar to those of groundwaters from the Wadi El Tarfa study (Sultan et al., 2000), the remaining Eastern Desert samples from the present study have isotopic characteristics that could be accounted for by mixtures of modern precipitation (i.e., flash flood waters) and Nubian aquifer water. A similar conclusion regarding the sources of groundwater in the Wadi Qena area was reached in a previous study by Hamza et al. (1999).

It must be pointed out that the data on the isotopic composition of precipitation in the Eastern Desert is sparse. In particular, it is difficult to evaluate the “amount effect” (Dansgaard, 1964; Clark and Fritz, 1997) whereby there can be a large variation in the isotopic composition of precipitation depending on the ambient humidity of the air through which the raindrops travel en route from their point of origin toward the land surface. Therefore, although it appears that many of the groundwaters in the Eastern Desert may have a dominant source in the Nubian aquifer, their isotopic characteristics do not necessarily preclude a relatively recent origin. Resolution of the question of the age of the Eastern Desert waters will be clarified when the chlorine-36 measurements (now in progress) are completed. Available data for tritium activities show that, aside from the presence of measurable tritium activities in a few of the Wadi Tarfa waters reported by Sultan et al. (2000), which indicated contribution of young (<50 years) meteoric water, tritium activities measured for 11 new samples of Eastern Desert groundwaters (see Table 2) revealed no measurable tritium, indicating residence times in excess of 50 years for these waters. All of these new tritium data were measured on samples that could represent mixtures of Nubian aquifer and recent waters, based on their isotopic compositions (i.e., dD values between –60 and –25). Therefore it may be concluded from these tritium data that if these waters are mixed then the more recent component (presumably having dD values near 0) may have a mean residence time of at least 50 years or more.

The absence of any data points between the cluster of Western Desert Nubian aquifer samples and Wadi Matuly E0005 ($\delta D = -58.7$) could indicate that the Nubian Aquifer in the Eastern Desert may have a different isotopic composition (somewhat less isotopically depleted) than in the Western Desert. The stable isotope data for Nubian Aquifer paelowaters from the Gulf of Suez area (Sturchio et al., 1996), including thermal springs Hammam Faraoun, Hammam Musa, Ayun Musa, and Ain Sokhna, indicate that these waters are significantly less depleted isotopically than the Western Desert paleowaters. The majority of the Eastern Desert waters are apparently intermediate between the Western Desert paleowaters and the Gulf of Suez area paleowaters, possibly reflecting a geographic trend in the isotopic composition of paleoprecipitation stored in the Nubian Aquifer. The apparent progressive enrichment in the isotopic composition from west (Western Desert) to east (Sinai) could reflect variable degrees of mixing between fossil water that precipitated during wet climatic periods and meteoric precipitation that is deposited during the interleaving dry climatic periods (e.g., nowadays). This hypothesis is supported by the patterns of modern precipitation. Currently, rainfall over the Nubian sandstone outcrops (recharge areas) in southern Sinai is considerable (~100 mm/yr) compared to their counterparts in the Western Desert that hardly receive any precipitation (0-5 mm/yr) (EMA, 1996; Nicholson, 1997; Legates and Wilmott, 1997). Precipitation in the Eastern Desert is intermediate between that reported for the Western Desert and for Sinai. The question of the true nature of the Eastern Desert Nubian Aquifer paleowater will be addressed further by consideration of comprehensive chemical analyses as well as isotopic analyses (in progress) of Cl stable isotope ratios, chlorine-36, and radiocarbon.

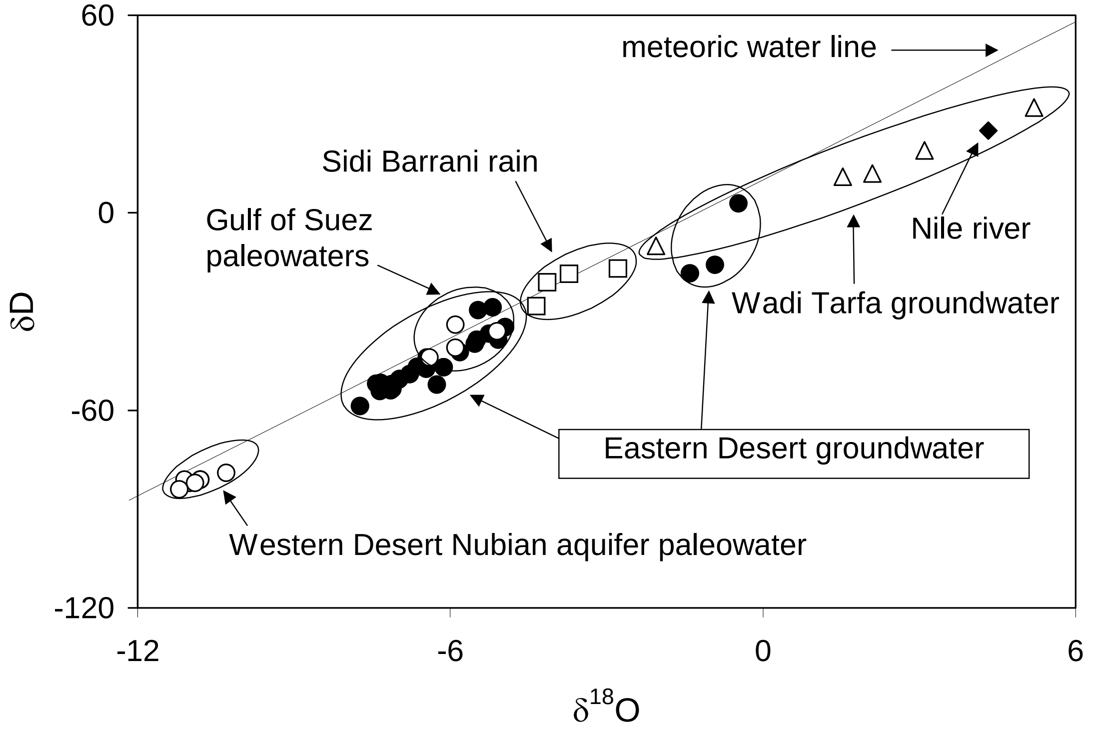

Figure 2 – *Stable isotope ratios of hydrogen (δD) vs. oxygen (δ^{18}O). Samples from Eastern Desert (this study) are shown as filled circles. Hollow symbols are data from other studies cited in text.*

Chemical Compositions of Groundwaters

Additional constraints on the mixing processes and solute sources in the Eastern Desert groundwaters are provided by the ionic compositions of the waters. Chemical data for the 31 water samples collected to date are listed in Table 1. The samples have generally low to moderate concentrations of total dissolved solids (~1,000–6,000 mg/L) dominated by a Na-Ca-Cl-SO_4 salt assemblage. It is useful to compare certain ionic ratios in groundwater with unfractionated marine aerosols (essentially seawater ion ratios) to assess sources of solutes. For example, the observed correlations between Na and Cl (Fig. 3) indicate that marine aerosols are most likely a dominant source of solutes. Marine aerosols may be deposited as dry salts on the land surface, and periodically dissolved and transported downward toward the aquifer during sporadic rainfall events. Some of these solutes may be concentrated by evaporation as halite, gypsum, and other salts within the soil layers and unsaturated alluvial deposits; these evaporaite salts may accumulate for many years, eventually being dissolved transported to the groundwater aquifer when a sufficiently strong rainfall event occurs.

Comparison of the chemical compositions of the Eastern Desert groundwaters with the Western Desert Nubian Aquifer paelowaters shows that the Western Desert paleowaters have much lower solute concentrations (Figure 3). Comparison of δD values vs. chloride concentrations shows that simple mixing between Western Desert paleowater and modern precipitation (i.e., flash flood waters, represented by sample WS-3 from Sultan et al. (2000)) cannot account for the range of groundwater compositions observed in the Eastern Desert (Figure 4). This implies that either the Nubian Aquifer endmember in the Eastern Desert has a different solute composition than that in the Western Desert, or there is an additional source of solutes that is not being accounted for by a simple 2-component mixture.

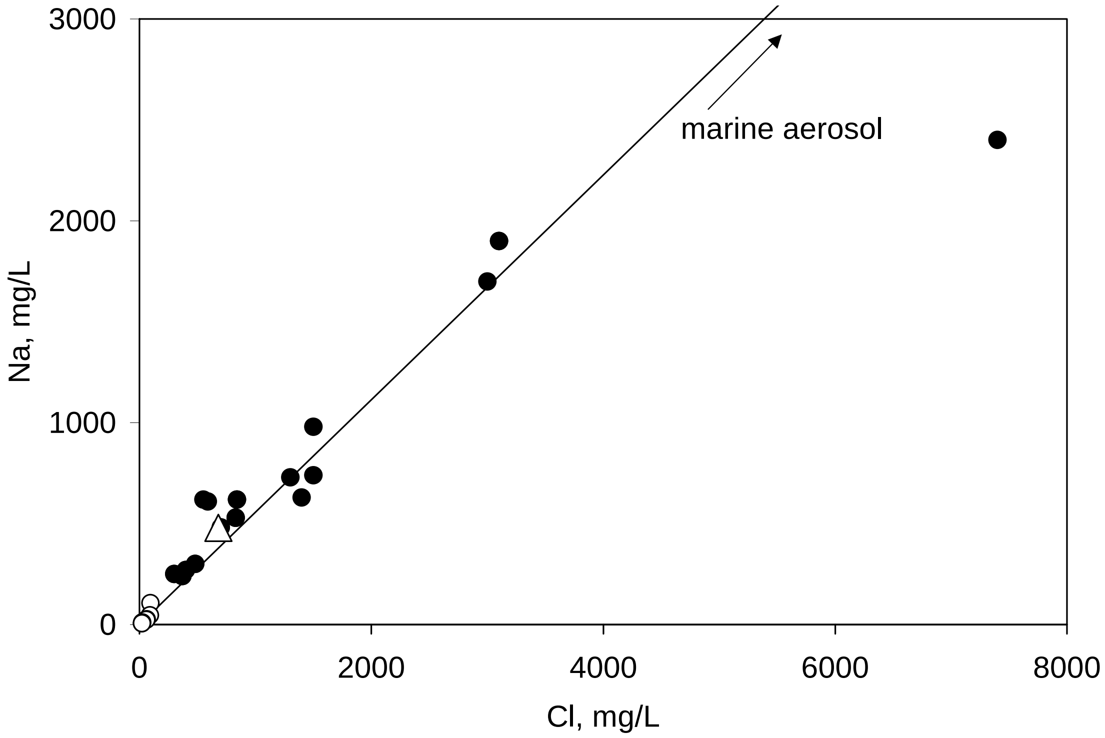

Figure 3 – *Na vs. Cl concentration in Eastern Desert groundwaters (filled circles) in comparison with Western Desert paleowaters (open circles) and modern precipitation represented by sample WS-3 from Wadi El Muhasham (open triangle).*

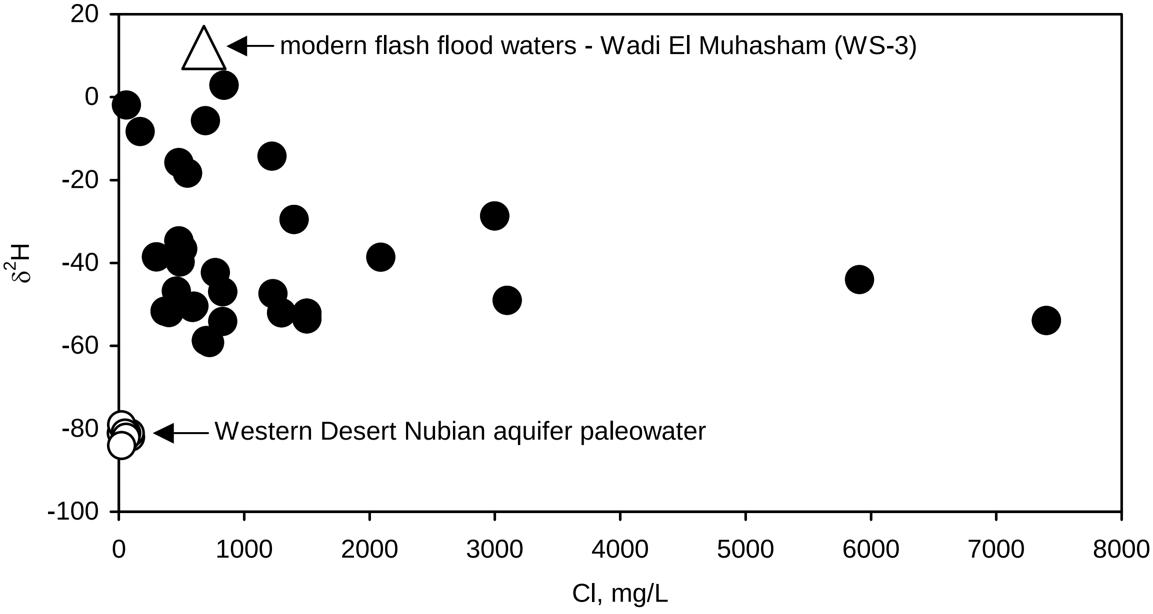

Figure 4 – *δD vs. Cl concentration in Eastern Desert groundwaters (filled circles) in comparison with Western Desert paleowaters (open circles) and modern precipitation represented by sample WS-3 from Wadi El Muhasham (open triangle).*

Stable Isotope Ratios of Chlorine

The origin of the dissolved chloride can be traced by measurement of the stable Cl isotope ratios, and this can serve as an indicator of the source of dissolved solutes in the groundwater. Chlorine stable isotope ratios ($^{37}Cl/^{35}Cl$, expressed as $\delta^{37}Cl$ values relative to the isotopic reference material, Standard Mean Ocean Chloride (SMOC)) are listed in Table 2 and shown vs. 1/Cl in Figure 5. These Cl isotope ratios are expressed in "delta" notation, defined as:

$$\delta^{37}Cl = \left[\frac{\left(\frac{^{37}Cl}{^{35}Cl} \right)_{sample}}{\left(\frac{^{37}Cl}{^{35}Cl} \right)_{standard,SMOC}} - 1 \right] \times 1000$$

Most of the samples have $\delta^{37}Cl$ values between about –0.6 and –0.4, like those of deep Nubian Aquifer paleowaters in the Western Desert (Patterson et al., 2005). As discussed by Patterson et al. (2005), the Nubian aquifer chloride having $\delta^{37}Cl$ values near –0.5 may represent chloride deposited with the precipitation that recharged the aquifer long ago (up to 1 million years).

However, the higher δ^{37}Cl values between about –0.4 and 1.0 indicate that there must be at least one other source of "heavy" chloride – and this is most likely to be either chloride leached from rocks or chloride deposited as halite salts at and near the land surface from marine aerosols. The fact that the samples having the higher Cl concentrations also tend to have higher δ^{37}Cl values is consistent with an additional (or totally different) Cl source for the most Cl-rich waters.

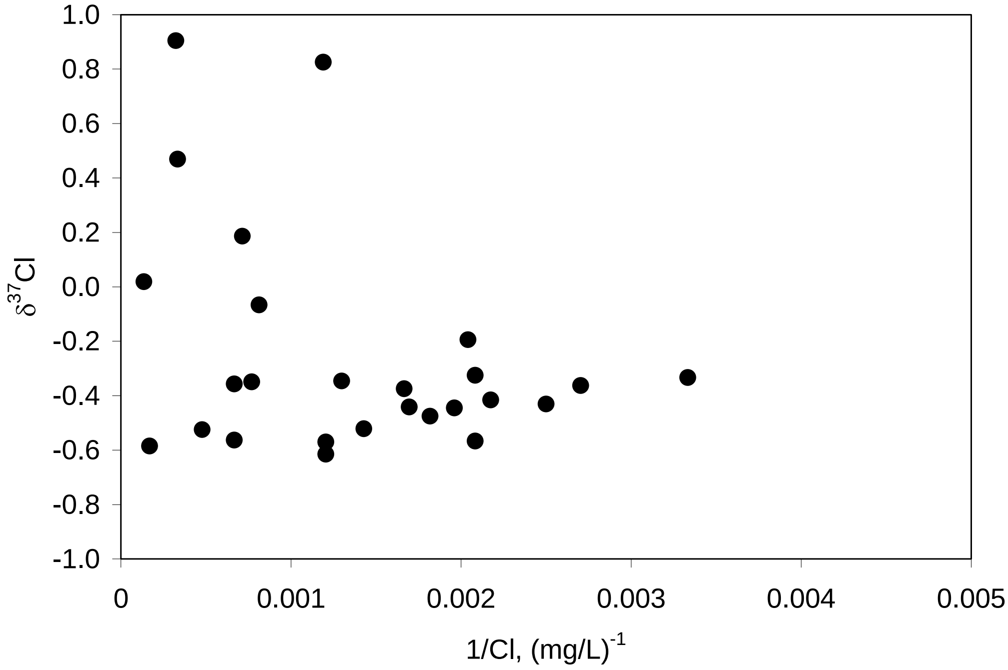

Figure 5 – *δ^{37}Cl vs. 1/Cl concentration in Eastern Desert groundwaters.*

Groundwater Dating

Both hydrodynamic and isotopic methods have been devised for dating groundwater. Groundwater age is defined as the time some unit of water has isolated from the atmosphere. Hydrodynamic models of groundwater age relate the velocity of groundwater flow as determined from physical properties of the host rock (e.g. permeability) and hydraulic head. In confined aquifers recharge and discharge are localized so flow paths from recharge to discharge can be modeled as smooth, linear "flow tubes". Isotopic methods of groundwater dating rely upon either the radioactive decay of some isotope present in recharge waters or radiogenic production of an isotope along the flow path to calculate age. Several isotopes have been used in studies of old to very old groundwater; ^{36}Cl, ^{4}He, and ^{14}C have been most widely applied. ^{36}Cl and ^{4}He are the most useful for very old groundwaters, but both present difficulties in quantifying subsurface input and (for ^{36}Cl) initial values (Davis et al., 1998). For this study of Eastern Desert groundwaters, we are using ^{36}Cl data to gain insights into the age and mixing relations. The data obtained here are compared with similar data for the Nubian Aquifer groundwater of the Western Desert (Patterson et al., 2005).

Groundwater Dating Using the Natural Radioactive Tracer ^{36}Cl

^{36}Cl ($t_{1/2}$=301±2 ka) has been a useful radioactive tracer for dating very old groundwaters since the 1980s. Atmospheric production by spallation of Ar ($^{40}\mathrm{Ar}(p,n\alpha)^{36}\mathrm{Cl}$) occurs largely in the stratosphere. The ^{36}Cl falls out primarily as wet deposition along with stable Cl from marine aerosols, and after concentration by evapotranspiration, it enters the groundwater system. Cl is considered a conservative groundwater tracer in that it is unaltered by biologic activity or most water-mineral interactions. In theory groundwater ages can be calculated from the decay of the atmospheric concentrations of ^{36}Cl, but in practice several factors complicate the use of ^{36}Cl to date very old groundwaters (Phillips, 2000).

One weakness of the ^{36}Cl method is the variance of the initial value of ^{36}Cl in recharge waters. The atmospheric residence time of ^{36}Cl is about a week, too short to allow complete mixing, so the atmospheric deposition of ^{36}Cl depends in part on local meteorological conditions. The dominant model of ^{36}Cl fallout, latitudinal dependence of atmospheric production of ^{36}Cl, may not accurately predict its concentration in recharge waters (Bird et al. 1991 and references therein). Keywood et al. (1998) found that local ^{36}Cl fallout in the southern hemisphere depends on troposphere-stratosphere interactions and tropical storm patterns and can be underestimated by the model by 40%. Furthermore, a greater distance between the recharge area and marine coastline causes lower Cl^- concentrations in precipitation, but higher ^{36}Cl/Cl ratios (Fabryka-Martin et al., 1987). Direct measurements of ^{36}Cl in modern local recharge are often used as initial values, but they do not address the problem of differential ^{36}Cl production through time. Davis et al. (1998) attribute the variance in atmospheric production of ^{36}Cl over the past 1 ma largely to changes in the intensity of the earth's magnetic field, but other factors could be solar cycles and a variable flux of cosmic rays to the atmosphere (Phillips, 1999). The variance in ^{36}Cl production is significant; Andrews et al. (1994) estimate that Pleistocene meteoric ^{36}Cl concentration was 1.5 times that of modern precipitation.

Another complication arises from the production of ^{36}Cl in the subsurface by the neutron flux caused by the decay of U and Th series elements. 98% of the subsurface production of ^{36}Cl occurs from $^{35}\mathrm{Cl}(n,\gamma)^{36}\mathrm{Cl}$ thermal neutron activation, with the spallation reactions $^{39}\mathrm{K}(n,\alpha)^{36}\mathrm{Cl}$ and $^{40}\mathrm{Ca}(n,p\alpha)^{36}\mathrm{Cl}$ also contributing (Fontes & Andrews, 1994). Concentrations of these elements in the aquifer matrix as well as of elements with high neutron absorption cross-sections (Li, B, and Gd) are necessary for the most accurate predictions of *in situ* production (Fontes & Andrews, 1994). However, modeling of ^{36}Cl behavior in groundwater has shown that subsurface buildup of ^{36}Cl increases with increasing Cl^- concentrations in the water itself such that the method fails to accurately date water as fresh as 75-150 ppm Cl^- (Park et al., 2002). A further consideration when using any radioactive tracer to date groundwater is the effect of mixing of waters of different ages and tracer concentrations. Mixing of two end members--young, ^{36}Cl-enriched water and an old, ^{36}Cl-depleted water—can cause a decrease in ^{36}Cl/Cl ratios that might otherwise be attributed to simple decay (Fontes & Andrews, 1994; Bethke, 2000; Park et al., 2002). In addition mass transport across formations with higher equilibrium ^{36}Cl/Cl ratios, higher salinities, or higher concentrations of U and Th can cause increases in aquifer ^{36}Cl concentrations.

Conclusion

Chemical and isotopic compositions of Eastern Desert groundwaters indicate two dominant water sources: (1) Nubian Aquifer paleowater, which occurs in areas underlain by the Nubian formation, and (2) recent meteoric water (flash flood water), which occurs in alluvial deposits underlying major wadis. In areas where the Nubian formation underlies thick alluvial deposits, and a fault structure allows for hydrologic conductivity, water produced from wells may be a mixture of Nubian Aquifer paleowater and recent meteoric water. Such wells may have a high and sustainable water yield. In areas where there is no Nubian formation, such as the Precambrian basement areas, water produced from wells is exclusively meteoric water that is stored in permeable alluvial deposits or perhaps highly sheared and fractured basement rocks that occur along major fault structures. Additional measurements of chlorine-36 (in progress) will help to resolve the question of the age of the Nubian Aquifer paelowater beneath the Eastern Desert – this water appears to have somewhat different chemical and isotopic characteristics than the Western Desert paleowaters.

Acknowledgments

The authors express their thanks the scientists and administration of the Ministry of Water Resources and Irrigation for their valued efforts in all aspects pertaining to this project and for the administration of Cairo University for their continued support. The activities for this project were supported by the UNDP program and the Global Environmental Facility International Water Program.

Table 1. Chemical analyses of Eastern Desert groundwaters

Name	Br, mg/L	Cl, mg/L	NO_3, mg/L	SO_4, mg/L	HCO_3, mg/L	Ca, mg/L	Mg, mg/L	K, mg/L	SiO_2, mg/L	Na, mg/L	Sr, mg/L
El Reshrash	0.26	3000	39	610	113	260	120	23	21	1700	18
El Reshrash	0.12	1400	11	290	103	210	92	14	21	630	12
Arab El Ashrafia	0.33	840	20	490	316	160	73	15	31	620	8.9
PW-Bir-10 Asyuti	0.8	480		120	187	87	19	7	24	300	1.6
PW-16 Asyuti	0.66	300		98	210	60	15	5.3	26	250	0.94
PW-15 Asyuti	13	3100	0.3	12	165	140	51	30	20	1900	2.4
PW-36 Asyuti	0.4	830	1.1	230	167	82	30	7.6	18	530	2.3
PW-1 Asyuti 2000	0.48	400	0.72	180	238	76	37	6.8	21	270	3.3
PW-5 Asyuti 2000	0.4	370	0.49	160	251	74	36	8.8	22	240	3.3
Wadi Matuly E0005	6.5	700		550	228	180	53	31	14	480	5.6
Wadi Matuly E0006	10	1500	3.9	1400	103	350	170	31	21	980	13
Wadi Matuly E0008	1	550	15	730	183	130	70	13	21	620	2.4
Wadi Qena E0009	2.8	590		320	310	32	7.9	15	22	610	0.95
Wadi Darah Abu Shaar El Bahary	7.6	1300		1900	172	630	140	16	24	730	13
Wadi Darah - Darah 4	7.6	1500	0.71	810	150	330	78	17	12	740	5.4
Wadi Darah - Abdul Aziz Farm	75	7400		1900	142	610	1100	44	20	2400	16
Field 2 Production Well	0.65	460	0.87	140	210						
Wadi Matuly Abdel Maksood Ranch	0.95	480	53.4	600	168						
Wadi Qena E0010	5.58	2090	0.11	1760	108						
Wadi Qena Artesian Well E0009	3.09	600	0.1	320	316						
Wadi Asyuti Field 1 PZ-1 deep	0.79	490	0.11	52	126						
Wadi Asyuti Field 1 PZ-2 medium	0.75	510	0.13	19	28						
Wadi Asyuti Field 1 PZ-3 shallow	0.33	830	0.19	120	35						
Field 3 PZ-1 shallow	0.76	770	5.25	210	165						
Field 3 PZ-2 medium	2.98	1230	1.49	160	217						
Field 3 PZ-3 deep	33.0	5910		52	283						
Sheikh El Shazly		1220	122	1370	219						
Bir Um Ghanam		60	23	100	244						
Hafafit		690	59	810	520						
Fawakhir		170	95	250	141						
Bir Laquiba		730		450	242						

Table 2. Stable isotope ratios of oxygen, hydrogen, and chlorine, and tritium activities in Eastern Desert water samples.

Name	Delta O-18	Delta H-2	Delta Cl-37	Tritium (TU)
El Roshashat	-5.19	-28.69	0.47	<1
El Reshrash	-5.47	-29.53	0.19	<1
Arab El Ashrafia, open	-0.47	2.85	0.83	
PW-Bir-10 Asyuti	-4.95	-34.68	-0.32	
PW-16 Asyuti	-5.49	-38.54	-0.33	
PW-15 Asyuti	-6.78	-48.99	0.90	
PW-36 Asyuti	-6.13	-46.95	-0.61	
PW-1 Asyuti 2000	-7.42	-51.96	-0.43	
PW-5 Asyuti 2000	-7.34	-51.67	-0.36	
Wadi Matulla E0005	-7.73	-58.71	-0.52	<1
Wadi Matuly E0006, open	-6.26	-52.14	-0.56	
Wadi Matuly E0008, open	-1.40	-18.34	-0.48	
Wadi Qena Artesian Well E0009	-6.99	-50.74	-0.44	<1
Wadi Darah Abu Shar El Bahary, open	-7.13	-52.00	-0.35	
Wadi Darah 4	-7.11	-53.53	-0.36	<1
Wadi Darah - Abdul Aziz Farm	-7.14	-53.90	0.02	
Field 2 Production Well	-6.64	-46.81	-0.42	
Wadi Matuly Abdul Maksood Ranch	-0.92	-15.75	-0.57	
Wadi Qena E0010	-5.08	-38.60	-0.53	
Wadi Qena Artesian Well E0009	-6.97	-50.40	-0.37	
Wadi Asyuti Field 1 PZ-1 deep	-5.53	-39.77	-0.19	<1
Wadi Asyuti Field 1 PZ-2 medium	-5.26	-36.64	-0.45	<1
Wadi Asyuti Field 1 PZ-3 shallow	-7.35	-54.15	-0.57	<1
Field 3 PZ-1 shallow	-5.82	-42.30	-0.35	<1
Field 3 PZ-2 medium	-6.46	-47.38	-0.07	<1
Field 3 PZ-3 deep in limestone 400m	-6.45	-43.98	-0.59	<1
Sheikh El Shazly	-2.72	-14.24		
Bir Um Ghanam	-1.99	-1.92		
Hafafit	-1.26	-5.65		
Fawakhir	-1.92	-8.27		
Bir Laquiba	-7.86	-59.20		

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