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Isotope based assessment of groundwater renewal in water scarce regions

Proceedings of a final Research Co-ordination meeting
held in Vienna, 18–21 October 1999

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FOREWORD

Assessment of available groundwater resources in water scarce arid and semi-arid regions is of substantial practical importance, since groundwater is often the only source of water in such regions to meet the ever increasing demand for water. Sustainable development and management of groundwater in these regions requires reliable estimates of the natural replenishment (renewal) rate of groundwater under present climatic conditions. The isotopic composition and chemical constituents of water infiltrating through the soil zone (unsaturated zone, or zone of aeration) into groundwater can be employed to determine the water infiltration rate and characterise the behaviour of moisture and contaminant transport.

Within the framework of the IAEA's sub-programme dealing with water resources, a Co-ordinated Research Project (CRP) on Isotope Based Assessment of Groundwater Renewal and Related Anthropogenic Effects in Water Scarce Areas was initiated in 1996, following a workshop in Wallingford, United Kingdom in December 1995, where the programme and details of the work to be undertaken along with field and laboratory procedures to be adopted were designed. Research Co-ordination meetings were held respectively in November 1997 in Vienna and in November 1998 in Sfax, Tunisia.

This publication is the result of the CRP and compiles papers summarising the results and findings of the applied field research carried out by the participating institutes, which were presented and discussed during the final Research Co-ordination Meeting held in Vienna from 18 to 21 October 1999. Stock could be taken of the impressive body of data which had been accumulated during the nearly three years of project activities, representing perhaps the most extensive survey of the unsaturated zone in arid to semi-arid regions ever undertaken.

It is expected that the information and overall findings of applied field research provided as a results of the CRP involving 44 benchmark sites at different regions of the world will be useful guidance material to scientists involved in groundwater resources assessment as well as to engineers and professionals involved in isotope field applications in groundwater systems.

The IAEA officer in charge of designing and co-ordinating all the related work in this CRP and responsible for this publication was Y. Yurtsever of the Division of Physical and Chemical Sciences.

EDITORIAL NOTE

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SUMMARY OF THE CO-ORDINATED RESEARCH PROJECT

INTRODUCTION AND BACKGROUND

The isotopic composition and chemical constituents of water infiltrating through the soil zone (unsaturated zone, or zone of aeration) into groundwater can be employed to determine the moisture transport in the unsaturated zone, thus enabling estimation of the water infiltration rate to the underlying aquifer. This was the basis on which this CRP was initiated in 1996, following a workshop in Wallingford, UK, in December 1995, where the programme was designed along with details of the work to be undertaken and field and laboratory procedures to be adopted. Research Co-ordination Meetings were held respectively in Vienna in November 1997, and in Sfax, Tunisia in November 1998. This CRP has built on previous experience on the use of isotopic and chemical tracers reported in the scientific literature.

The overall results obtained from three years of applied field research related to study of moisture transport dynamics and estimation of natural recharge through use of isotope/hydrochemical depth profiles of the soil moisture in the unsaturated zone were presented and discussed at the final Research Co-ordination Meeting held in Vienna from 18 to 21 October, 1999. A total of 44 sites were involved in the project on which detailed information on physiography, lithology, rainfall, unsaturated zone moisture content and a variety of chemical and isotopic determinants is now available. Reliable recharge estimates were obtained in many areas, especially in predominantly sandy sediments, producing values ranging from fractions of a millimetre to tens of millimetres per annum.

ACHIEVEMENTS AND RESULTS

A number of benchmark sites on which detailed information on physiography, lithology, rainfall, unsaturated zone moisture content and a variety of chemical and isotopic determinants is now available. Much of the data has been analysed to provide recharge rates, producing values ranging from fractions of a millimetre to tens of millimetres per annum. These research results summarized in the table given at the end of this section, represent an important new database for the unsaturated zone. In some cases, information was obtained on the underlying saturated zone, the ultimate resource, the assessment of which formed the aim of the project.

In the motivation for this project it was anticipated that the most important parameter to emerge from the dozens of isotopic profiles produced during the CRP is ground water recharge. In the event, arguably with the exception of only one project, recharge estimates were based on the chloride concentration in the moisture and its vertical variability. Isotopic parameters in themselves provided valuable information, largely complementing these estimates. Environmental tritium was seen as a key isotope with which to assess and calibrate downward moisture flux. It was expected that the thermonuclear peak might still be visible in some profiles. Various profiles of tritium content demonstrated time constants of the order of decades. With the exception of China, where the unsaturated zone is composed of fine-grained loess material, the lack of resolution in the tritium profiles precluded reasonable estimates of downwards water flux rates from being made. In certain instances, the tritium data was even found to apparently contradict conclusions based on chemical and other isotopic indicators.

Classically, chloride is regarded as a simple, conservative solute tracer of water transport in the sub-surface. As such, the preparatory workshop in 1995 recommended that chloride profiles, along with deuterium profiles where possible, should first be obtained to act as an initial indicator of the transport of water in the unsaturated zone in the various project areas. More detailed investigations with e.g. tritium which is not so readily measured, were to follow. It was established certain problems remained even relating to the application of chloride including the reproducibility of its extraction from the field samples and analytical measurement especially at low concentrations. Reliable recharge estimates were, however, obtained in many areas using the chloride method, especially in predominantly sandy sediments.

Careful consideration of the large body of data obtained from a wide variety of environments led to the conclusion that subtle matrix conditions in the unsaturated zone, may have influence on soil water movement at the detailed level. In general, the upper 2-4 m of most profiles showed evidence of recycling of moisture and chloride with evidence of macro-pore or bypass flow but below this depth most profiles showed homogenous movement. In few cases the results of chloride and tritium appeared incompatible and it was uncertain if this was due to field or analytical problems. The results from some countries (e.g. Senegal, Tunisia, Jordan) demonstrate that oscillations in the chloride profile reflect different recharge rates over decadal or longer time scales and support the hypothesis that, like tritium profiles, the unsaturated zone may be used in favourable circumstances to record recharge history. Since the drilled profiles in principle represents only one point, it was considered early on in the CRP how these data might be used to interpret the lateral, spatial variability of the profiles. This was achieved in several of the individual projects, sometimes on a scale of tens of metres, and demonstrated the influence of vertical variations in matrix characteristics that existed by considering only individual sites. The use of several profiles at same sites using both chemical and isotopic data improved the earlier concepts of unsaturated zone moisture transport.

Solutes such as chloride, although conservative, may become uncoupled from the solvent (water) under the influence of large changes in moisture content in arid environments. This tends to mask some of the complexities of moisture behaviour. The isotopes of the water molecule are influenced critically by such processes, and the effects of e.g. evaporation near the ground surface and aspects of vapour, rather than moisture, transport have been identified. The detailed interpretation of such phenomena has proved to lie beyond the scope of most of the work done during this three year project.

It was foreseen in this CRP that isotopic tracers would lead to the provision of information such as moisture movement, recharge rates and solute transport. A major feature which emerged is that isotopic data highlight the complexities of the processes which had previously only imperfectly been appreciated and in certain instances been glossed over.

In most of the deeper profiles obtained, a zone of rapidly changing conditions, usually extending to some metres depth, gives way to a deeper zone of more or less steady-state conditions. Whereas nitrate was formerly seen as a pollutant, the transport of which was to be assessed, it emerged in various studies that, in the zone of steady state, it acts as a conservative tracer, similar to chloride.

The sensitivity of chloride balance approaches to analytical and methodological uncertainties needs closer attention. Chloride should be included in the parameters to be measured in future on samples gathered under the GNIP programme. This recommendation recognizes the special care which might have to be exercised in the sampling, handling and analytical procedures. The significance of dry deposition of chloride is to be taken into consideration and needs to be assessed at representative sites.

In the light of the difficulties in interpreting tritium profiles which do not display an identifiable “bomb” peak, it is recommended that tritium profiles should continue to be taken in favourable locations (e.g. sandy porous media) down to the water table. This would allow for a tritium balance to be set up, and by implication, the calculation of water transport.

Although the present CRP led to the recognition of the complexity of the unsaturated zone, it is strongly recommended that future attention be given to the problems highlighted, on the basis both of the existing and extremely valuable data set as well as future studies. Here, some of the benchmark sites identified could well be revisited. For any new sites, the following factors are seen to be crucial pre-requisites:

- the proximity of a reliable rainfall measuring and collecting station;
- a fair prior knowledge of conditions in the unsaturated zone, in order to avoid problems in sample collection and excessive complexities in data interpretation;
- adequate access to the underlying saturated zone (the resource) the data on which should act as a link with the overlying unsaturated zone data and also to generalize conclusions from point observations (the profiles) to the wider regional groundwater body.

Although modelling was not part of the aims of the CRP as originally conceived, physical models or moisture and solute movement could be applied in future, as benchmark sites are now available and a large body of analytical and other data on these sites is an important product of the project.

COUNTRY/REGION	Profile No.	Coring Date month/year	Total Depth (m)	Profiles Obtained (i.e. Cl, H-2, O-18, H-3, Br, No3, etc)	Mean An. Precip. (mm)	Cl conten in rain (mg/l)	Recharge estimated (mm/year)	Remarks
CHINA								
Inner Mongolia	CN/97	5/1997	15.15	Cl, H-2, O-18, H-3	360	2.2	47	
Shannxi Province	CN/98	5/1998	15.5	Cl, O-18, H-3	550	10.2	68	
EGYPT								
Northern Sinai peninsula	Rafaa-1	8/1997	20	Cl, H-2	300	16	24	Homogeneous sand
coastal strip, Shiekh Zowied	Rafaa-2	8/1997	20	Cl, H-2	300	16	18	Fine sand and silt
and Rafaa area	Rafaa-3	8/1999	20	Cl, H-3	300	16		
	Rafaa-4	8/1999	20	Cl, H-3	300	16		
INDIA								
Barmer District of Western	S1	4/1998	15	Cl, H-2, O-18, H-3	240	2	14.5	
Rejasthan-Sihania	S2	4/1999	15	Cl, H-2, O-18, H-3, NO3, F, SO4	240	2	18.2	
Lakrasar	L1	4/1999	7	Cl, H-2, O-18, H-3	240	2	12.3	
Srafki Danl	SD1	2/1997	12	Cl, H-2, O-18, H-3	240	2	20	
JORDAN								
Quwayra	S1	8/1997	10.5	Cl, H-2, NO3	65	10.5	0.03	No modern recharge
Jarash	S2	11/1997	21.5	Cl, H-2, NO3	480	10.2	28.4	
Jarash	S3	10/1998	17	Cl, H-2, NO3	480	10.2	8	Evap.during samp?
Azraq	S4-1	9/1999	7	Cl, NO3, SO4	67	60.6	0.2	(0-4.5 m)
Azraq	S4-2	9/1999	7	Cl, NO3, SO4	67	60.6		
Azraq	S4-3	9/1999	6.5	Cl, NO3, SO4	67	60.6	1.5	(0-4.5 m)

COUNTRY/REGION	Profile No.	Coring Date month/year	Total Depth (m)	Profiles Obtained (i.e. Cl, H-2, O-18, H-3, Br, No3, etc)	Mean An. Precip. (mm)	Cl conten in rain	Recharge estimated (mm/year)	Remarks
JORDAN (Continued)								
Azraq	S4-4	9/1999	11	Cl, NO3, SO4	67	60.6		No modern recharge
MEXICO								
Mesilla Bolson, Chihouhua	1	1-6/1997	58	Cl, H-2, NO3	230	1	0.24	Eval. int. 8-40 m
Guaymas, Sonora	1	2/1999	5.5	Cl, H-2, NO3	320	3.4	0.16	Eval. int. 1.5-5.5 m
Guaymas, Sonora	2	2/1999	8.5	Cl, H-2, NO3	320	3.4	0.11	Eval. int. 1.5-8.5 m
NIGERIA								
	MF1	11/1997	16.5	Cl, NO3, Br	389	1.72	0.16	Silt/clay profile
	MF2	5/1998	16	Cl, H-2, O-18, NO3, Br	389	1.72	0.16	Silt/clay profile
	MG	12/1998	16.25	Cl, H-2, O-18, NO3	389	1.72	22	Sandy profile
SAUDI ARABIA								
Qasim Area	CRP-1	4/1997	18	Cl, H-2	133	13.31	1.8	
SOUTH AFRICA								
N-W Province	BH-10	7/1997	18	Cl, O-18, H-3	309	1		
	BH-11	7/1997	15	Cl, O-18	309	1	1.7-4.9	(Based on Cl)
	BH-12	7/1997	2.8	Cl, O-18	309	1		
	BH-13	7/1998	22	Cl, H-2, O-18, H-3	309	1	13	(based on H-3)
	BH-14	7/1998	8	Cl, O-18	309	1		
	BH-15	7/1998	8	Cl, O-18	309	1		

COUNTRY/REGION	Profile No.	Coring Date month/year	Total Depth (m)	Profiles Obtained (i.e. Cl, H-2, O-18, H-3, Br, No3, etc)	Mean An. Precip. (mm)	Cl conten in rain	Recharge estimated (mm/year)	Remarks
SENEGAL								
Louga and Njame region	NL-1	7/1998	45	Cl, H-2, NO3, SO4	290	3.2	18	
	NL2	3/1999	24	Cl, H-2, H-3, NO3 SO4	290	3.2	9.8	
	L-23	6/1995	37	Cl, H-2, NO3, SO4	290	3.2	78.3	
SYRIA								
Damascus Oasis	I	9/1996	20.6	Cl, H-2, NO3	220	7.25	1.9 5.9	Eval. int. 0-14 m Eval. int.14-20.6 m
	N	6/1997	4.75	Cl	220	7.25	1.6	
	A	6/1998	5.85	Cl	220	7.25	1.1	
	B	7/1998	5	Cl	220	7.25	1.6	
	E	10/1998	5.5	Cl, NO3, NH4	220	7.25	0.25	
	K	10/1998	5.25	Cl, NO3, NH4	220	7.25	2.6	
	L	10/1998	1.5	Cl	220	7.25	2.8	
	C	10/1998	1.8	Cl	220	7.25	1.1	
Tartous	H	9/1996	2.35	Cl	885	21.26	14.6	
TUNISIA								
Tozeur	TOZ-5	11/1997	14	Cl, H-2	100	20	0.55	
Nefta	1	4/1998	13.5	Cl, H-2, O-18, H-3	94	7	0.7	

Investigation of the unsaturated zone in semi-arid regions using isotopic and chemical methods and applications to water resource problems

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Abstract. Isotopic techniques combined with chemistry can provide comprehensive information on groundwater recharge and recharge history, as well as on environmental and climatic change. Examples of integrated use are reviewed from studies in Senegal and Cyprus as well as Sudan. Tritium provides calibration for the wider use of Cl as a tool for larger scale recharge estimation in low rainfall areas. A recharge history is preserved in the unsaturated zone in favourable locations where homogeneous unsaturated flow predominates. Recharge variations taking place at the decadal scale tie in well with instrumental records and extrapolation indicates records may exist over centuries or millennia. Results from the CRP, from Nigeria, Tunisia, Jordan and Mexico have been modelled against local rainfall records and chemistry to give a reasonable correlation with recharge events over various timescales from 30 to 50 000 yr.

Introduction

Geochemical techniques using chloride and tritium contained in unsaturated zone moisture profiles are becoming established as a reliable tool for measurement of direct (or diffuse) recharge rates in semi-arid regions. Tritium has been widely used in temperate zones and less commonly in arid zones (Edmunds and Walton 1980; Allison and Hughes 1978; Aranyossy and Gaye 1992; Gaye and Edmunds 1996) to measure recharge but there are limitations to its use, notably the cost and specialised sample preparation, the radioactive decay (half life 12.3 years), the cessation of thermonuclear testing, and the loss of tritium in the vapour phase during evapotranspiration. Nevertheless the position and shape of the tritium peak in unsaturated zone moisture profiles provides convincing evidence of the extent to which 'piston displacement' occurs during recharge as well as providing an estimate of the recharge rate.

In contrast to tritium, chloride inputs from atmospheric deposition are conserved in the soil zone and are concentrated due to the loss of moisture by evapotranspitration. The accumulation of chloride may therefore be used as a basis for recharge estimation. Although the timing of the tritium spike is well known, use of chloride relies on knowing the depositional flux and hence details of present and past distributions in rainfall (Edmunds and Gaye (1994), Allison et al. (1994).

The accumulation of chloride in the unsaturated zone under piston flow conditions, together with stable isotope data may also provide a record of past recharge and to help reconstruct the antecedent climatic conditions. The unsaturated zone therefore may act as an additional climatic archive in continental areas where records are scarce and supplement those obtained from lake sediments for example. Such records may be found in Africa covering the century or millennial scale with typically decadal resolution (Cook et al 1992), although much longer unsaturated zone records in excess of 10^5 yr may be preserved in some arid regions (Tyler et al 1996).

The unsaturated zone may in addition record environmental change over similar time periods, especially the influence of vegetation cover and subsequent removal by humans and the onset of agricultural development. This is seen especially in the nitrate concentrations preserved in the unsaturated (and saturated zones) beneath continental areas (Edmunds and Gaye 1996; Edmunds 1999).

The objective of this paper is to briefly summarise existing knowledge on the use of isotopic and inert chemical tracers in unsaturated zone investigations of a) groundwater recharge, b) recharge history and c) environmental change. Examples used are from the recent literature as well as some results gathered within the present programme of research co-ordinated by the IAEA.

Methods and theory

The chloride balance method has now been successfully used in a range of environments to determine recharge, for example in north Africa and the Middle East: Edmunds and Walton (1980), Suckow et al.(1993), Edmunds and Gaye (1994), Bromley et al.(1996); in Australia: Allison and Hughes (1978), Allison (1994); in India: Sukhija et al.(1988); in southern Africa: Gieske et al.1990) and in north America: Stone (1987), Phillips (1994), Wood et al.(1995). Details of the chloride method have been described elsewhere (Edmunds et al.1988; Herczeg and Edmunds 1999) but a conceptual model and summary of the measurement of recharge and recharge history are given in Figure 1 based on a profile at Akrotiri, Cyprus.

Samples of moist sand are obtained by auguring or other dry drilling techniques at regular intervals through the unsaturated zone. Moisture contents are measured gravimetrically and chloride is determined on samples obtained either by centrifugation (Kinniburgh and Miles 1983) or by elutriation with distilled water (typically adding 30ml water to 50g sediment). Chloride (and nitrate) have been measured with high precision using colorimetric methods. Other analytical methods such as anion chromatography may be suitable for chloride providing low level Cl (#0.5 mg l^{-1}) can be determined with suitable precision – notably in samples of continental rainfall.

Rainfall (total deposition) inputs must be known. In the studies discussed here an average of the mean rainfall and weighted mean chloride concentrations have typically been obtained over three or more seasons. Errors associated with rainfall measurement and the spatial variability of rainfall are likely to constitute the largest uncertainty in recharge estimation using chloride and an assumption must be made that the average atmospheric chloride flux has remained constant with time at a given location.

Groundwater at the water table taken from shallow wells may also used to obtain information on recharge and in conjunction with the unsaturated zone profiles can provide estimates of the spatial variability of recharge (Edmunds and Gaye 1994).

Estimation of modern recharge from profiles

Representative single profiles from three semi arid regions - the Mediterranean (southern Cyprus), west Africa (Senegal) and east Africa (Sudan) are shown in Figures 2-4 which cover the range of conditions from active recharge to effectively zero recharge at the present day.

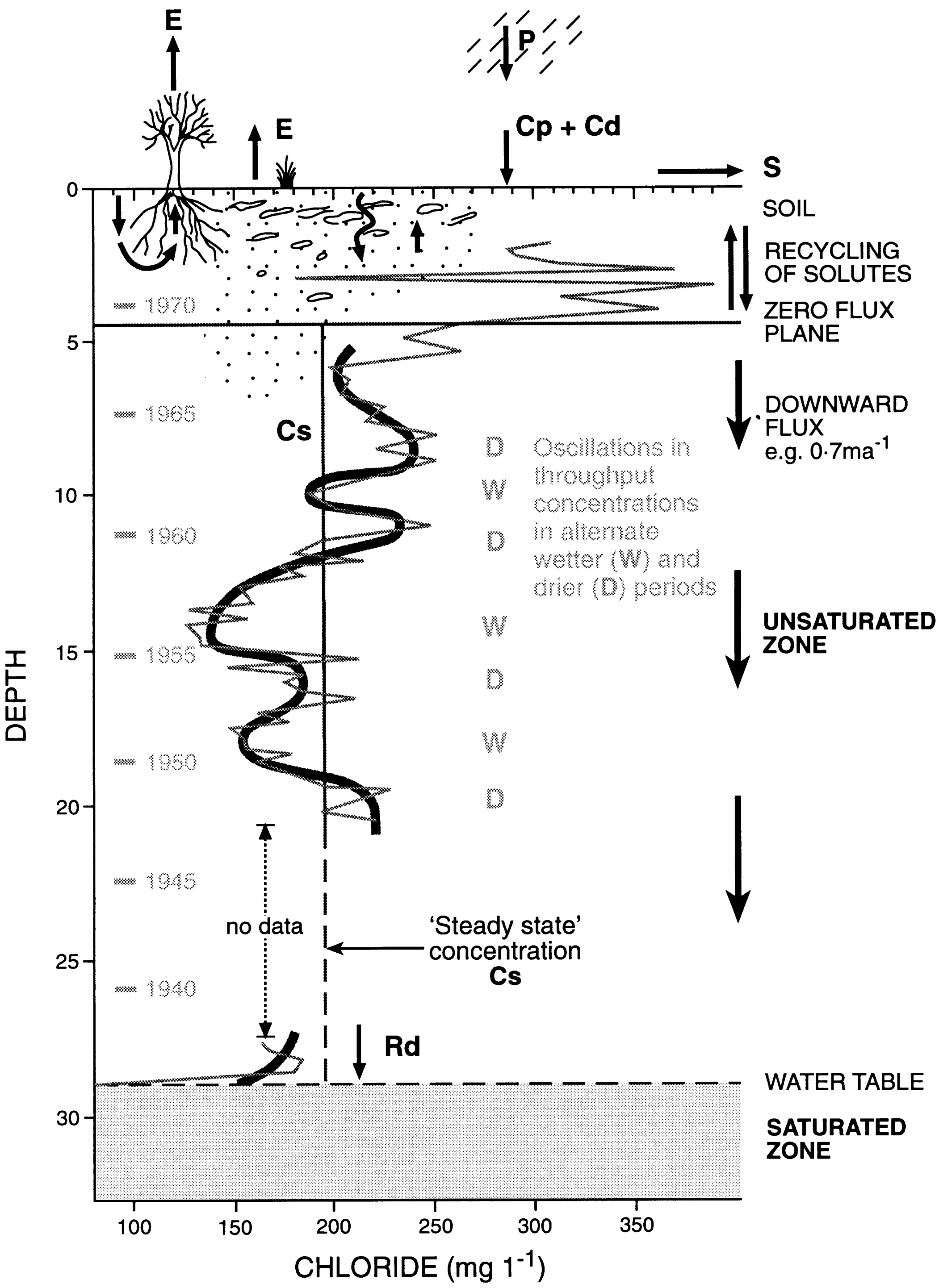

Figure 1. The movement of water and solutes through the unsaturated zone. Estimation of recharge and use of Cl profiles to indicate recharge history. Based on a profile from Akrotiri, Cyprus.

The data from Cyprus are from the Akrotiri peninsular from Recent dune sediments and chloride is shown together with tritium profiles (Figure 2) from the same percussion drilled borehole these are described in greater detail in Edmunds et al (1988). The chloride concentrations below the zero flux plane (around 2 m in grass vegetation) oscillate about mean values (C_S) in each profile of 119 and 122 mg l^{-1} respectively. These oscillations have been interpreted in terms of seasonal variations related to periods of wet and dry years. The mean concentrations can be interpreted to give values of recharge (see Fig.1) respectively of 56 and 55 mm yr, using a three year mean rainfall concentration of 16.4 mm yr at this coastal site. Tritium profiles serve to confirm the recharge rates given by chloride, the peaks marking the position of the 1963 thermonuclear fallout maximum in the rain; the recharge rates obtained using the amount of moisture above the tritium peak are 52 and 53 mm yr^{-1} respectively. The shape of the tritium peaks also confirms that downward movement of moisture (and solutes) is homogeneous with little or no by-pass flow.

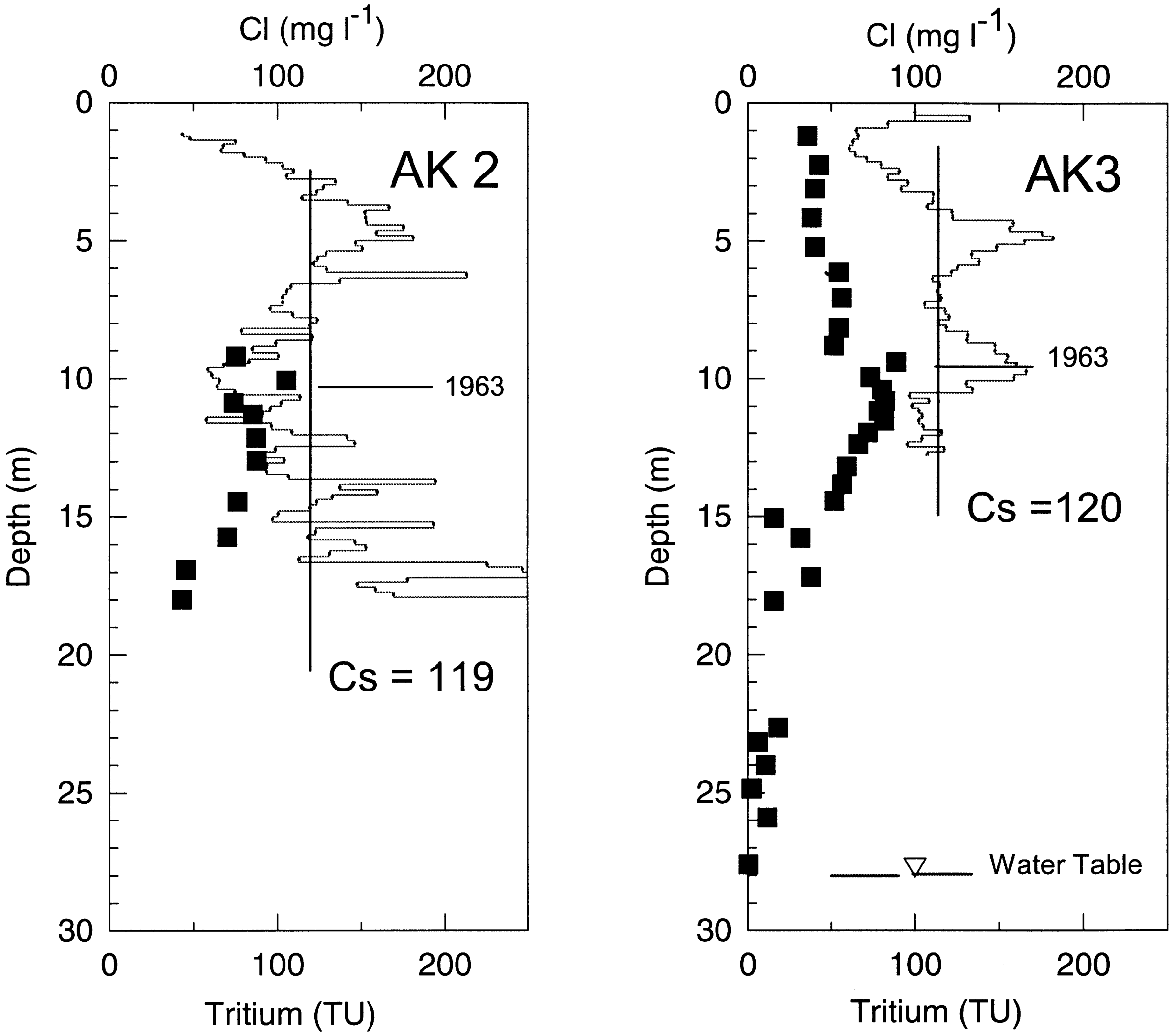

Figure 2. Two profiles from Akrotiri, Cyprus for which both Cl and tritium have been measured. The position of the i963 tritium peak is indicated. Cs indicates the mean concentration of chloride in the unsaturated zone moisture over the indicated distance.

An example of an integrated study from Senegal using Cl, stable isotopes and tritium is given in Figure 3, based on results given in Gaye and Edmunds (1996) and Aranyossy and Gaye (1992). Samples were obtained from Quaternary dune sands where the water table was at 35m and where the long term (100 year) rainfall is 356mm yr (falling by 36% to 223mm since 1969 during the Sahel drought). The tritium peak defines clearly the 1963 peak as well as demonstrating the excellent approach to piston displacement. A recharge rate of 26mm yr^{-1} is indicated. The Cl profile shows oscillations due to variable climatic conditions (see below) but a mean concentration of Cl (23.6 mg l^{-1}) corresponding to a recharge rate of 34.4 mm yr^{-1}, in close agreement with the tritium is calculated using a value for rainfall Cl of 2.8 mg l^{-1} (average rainfall 290mm yr^{-1}). The stable isotope values are consistent with the trends in recharge rates indicated by Cl, the most enriched values corresponding to high Cl and periods of drought, but the stable isotopes are unable to quantify the rate of recharge, unlike Cl and ^3H.

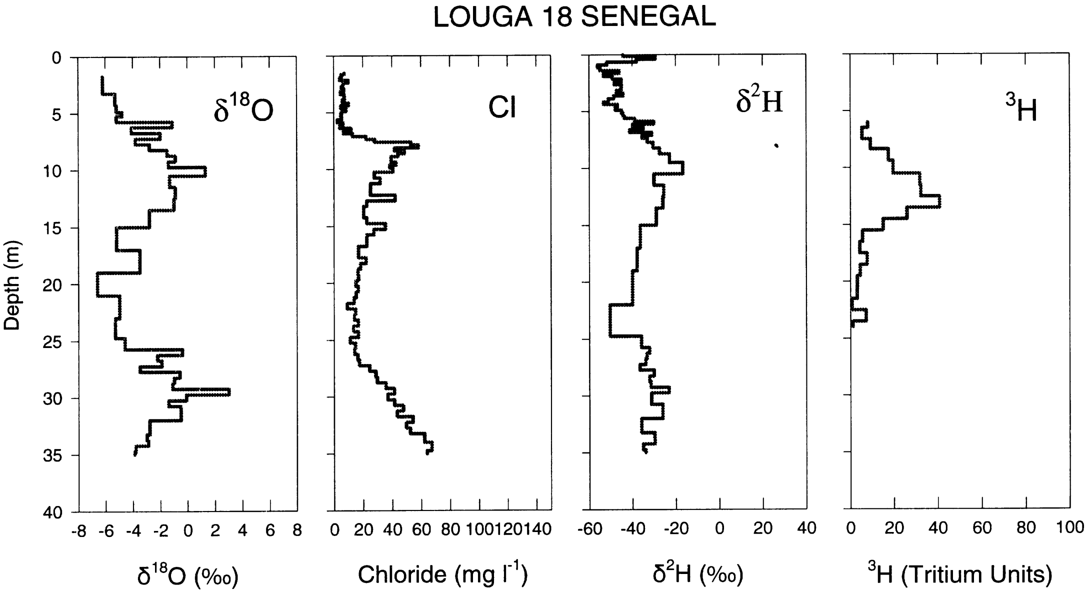

Figure 3. Intercomparison of data for $\delta^{18}O$ δ^2H, Cl and ^3H for one site near Louga, Senegal.

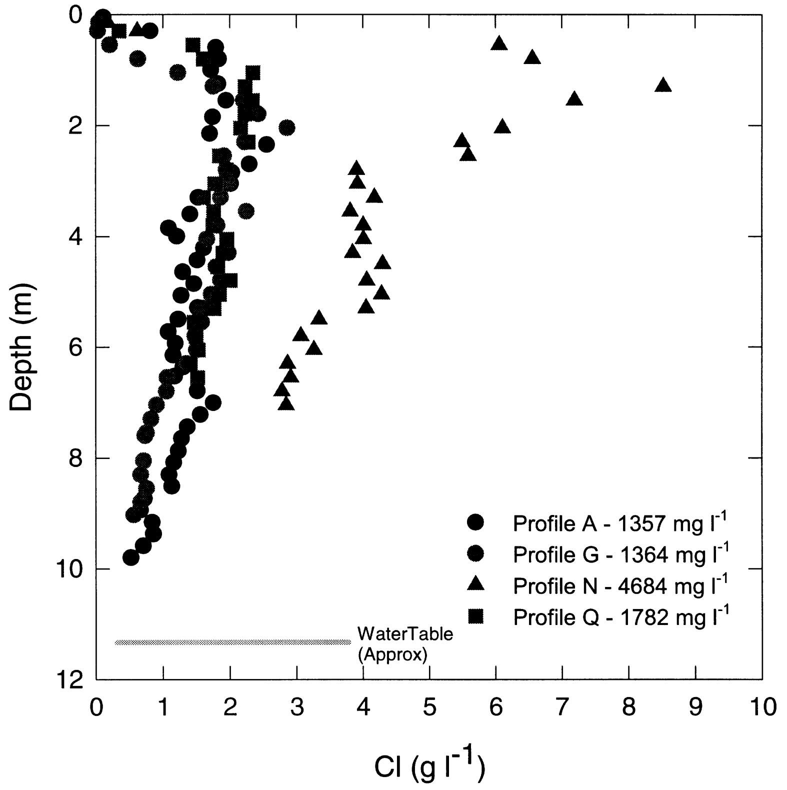

Figure 4. Four profiles of chloride in the unsaturated zone from Abu Delaig, Butana region, Sudan.

Further profiles from Louga in north-west Senegal (Edmunds and Gaye 1994) illustrate the spatial variability of recharge within one site (1 km^2). The average chloride concentrations of 7 separate profiles at this site is 82 mg/l giving a spatial average of 13mm/yr. Having established that all the Cl in this region is atmospherically derived, it is therefore possible to extrapolate the unsaturated zone data to determine the spatial variability of recharge at a regional scale using data from shallow dug wells. Data from 120 shallow wells over an area of 1600 km^2 were used to calculate the distribution of recharge. The regional recharge varies from 20 to <1mm/yr, corresponding to a renewable resource of between 13 000 and 1100 m^3/km^2/yr (Edmunds & Gaye 1994).

A limiting condition must exist in arid regions where rainfall becomes too low and other factors such as soil type intervene to inhibit any regional or diffuse recharge. Under this condition the unsaturated zone will become saline and geochemical reactions will lead to the formation of indurated crusts. The data from Sudan (Figure 4) are from near Abu Delaig in the Butana region, north east of Khartoum where prior to 1969 the mean annual rainfall was 225mm but for the following 15 years was only 154mm (Edmunds et al. 1992). The profiles were drilled in interfluve areas comprising sandy colluvial clays of probable Quaternary age overlying Nubian (Cretaceous) sandstone. The four profiles are very similar in their shape with mean chloride concentrations which range from 1357 - 4684 mg l^{-1} corresponding to recharge rates of <0.1 to 0.78 mm yr^{-1}. This is effectively zero and water in the unsaturated zone in this part of Sudan which is 25m thick must be in storage or have been in transit for around 2000 yr. The shapes of the profiles are complex and suggest that in the top 3m recently recharged water has mixed with water being recycled due to evaporation during drier interludes; in the lower part of the profile fluctuations of the water table where less saline water is found have probably led to a diffusion gradient. Similar high concentrations of chloride and low recharge rates have been recognised in Australia (Allison and Hughes 1983) and in southern USA (Phillips 1994).

Recharge history at the century to millennium scale

Under conditions of piston flow solute (or tritium) inputs derived from the atmosphere should be displaced at regular intervals from the soil horizon into the unsaturated zone, with higher solute concentrations corresponding to lower recharge. The theory of the movement of solutes through the unsaturated zone and the transmission of solute peaks corresponding to recharge episodes has been described and critically reviewed by Cook et al (1992). Variations in chemistry will be preserved only if the time scale for hydrological change is large relative to the diffusive timescale. Using the model developed by Cook et al. (1992) a persistence time may be defined which represents the time that it takes for the relative difference in solute (chloride) concentration to be reduced to 20% of its original value.

In Figure 5 the persistence time is shown for solute (chloride) and isotopic (eg δ^{18}O or tritium) profiles for events of 0.5, 5, 20 and 100 years and for recharge rates of 0.1 - 160mm/yr. The situation is shown for two values of moisture content. It is clear that seasonal fluctuations will persist for more than one year for a water content of 0.10 only when the recharge rate is above 50mm/yr (or at a water content of 5% when the recharge is above 20mm/yr). However if the oscillations have a timescale (half wavelength) of 5 years then these will persist for more than 50 years if the recharge rate is more than 20mm/yr and for more than 100 years if the rate is greater than 40mm/yr. A 20-year event such as the recent Sahel drought should persist at a recharge rate of 10mm/yr and at a moisture content of 5%

(typical of fine grained sands) for around 800 years. The corresponding isotopic (water) signal will be significantly less due to diffusion also in the gas phase.

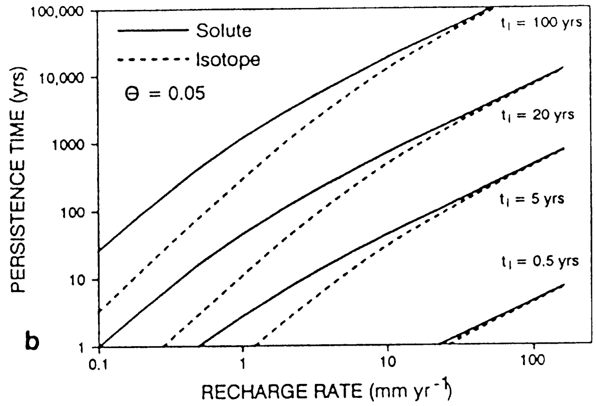

Figure 5.Persistence times of variations in solute (chloride) and isotope concentrations in the unsaturated zone before they are smoothed by diffusion and dispersion for volumetric moisture contents of 10% and 5%. For definition of persistence time see text. Adapted from Cook et al. 1992.

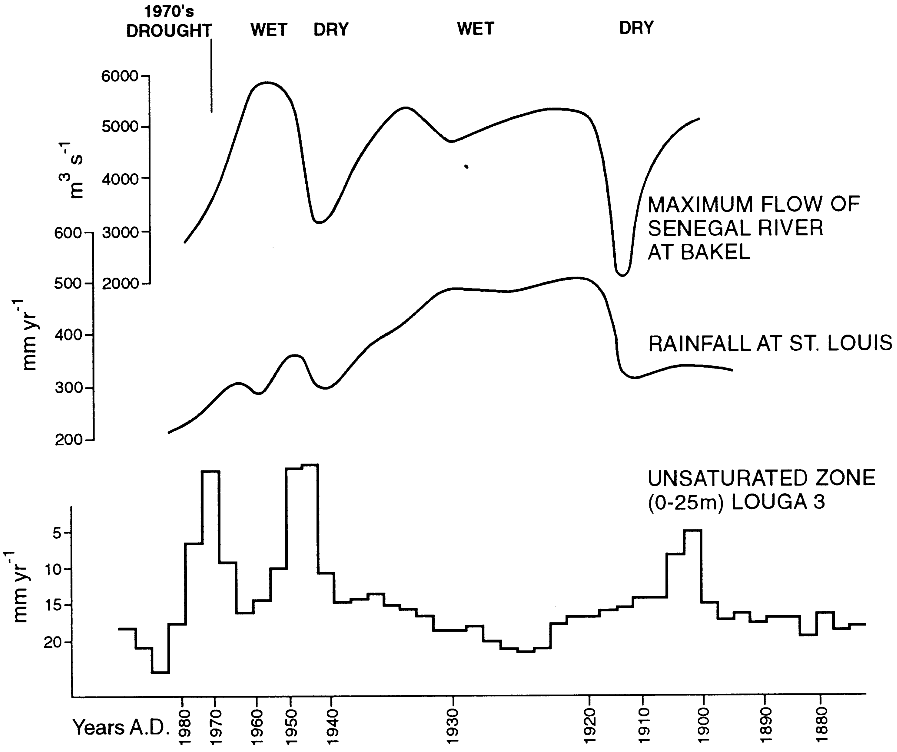

Figure 6. Comparison of the calibrated L3 profile (Louga, Senegal) with the climatic record of the last century as given by the rainfall record of St Louis and the flow of the Senegal River at Bakel.

Several profiles obtained from N Senegal have been interpreted successfully as archives of recharge, climatic and environmental change for periods up to 500 years. Over the past 100 years, good corroboration is provided by instrumental records for rainfall and river flow. In Figure 6 one profile (L3) has been calibrated using the recharge rates and moisture contents according to the formula in Figure 1, subdividing the data according to intervals of high and low chloride. The profile record is 108 years, assuming that recharge over this period is representative of the 3-year average (2.8mg/l) measured in this study. Assuming that the piston flow model applies, the peaks in Cl at 4-6m and 6-13m should correspond to periods of drought from 1970 and also in the 1940's. Another peak in the 1900's also reflects a drought period. The unsaturated zone profile is compared with the rainfall record at St Louis (some 80 km from the research site) dating back to the 1890's (Olivry 1983) and with the Senegal River with records over a similar period (Gac 1990). Whereas the correlation with the rainfall records is moderately good, the correlation with the river flow, representing the regional influence is better. The correspondence with the main wet phase from 1920-1940 is well shown in all sets of data. During the dry episodes the recharge rate reduced to around 4mm/yr but during the wet phases this rose to as high as 20mm at this site. An exact correlation between the various archives would not be expected for reasons stated above, the possibility of some by-pass flow, dispersion of small scale events and the likelihood that some variation of rainfall chemistry over the long term might be expected. In addition the rainfall and river flow data also contain possible errors. Nevertheless similar records are found in other profiles (Cook et al 1992; Edmunds et al 1992) and provide confidence to extrapolate further over longer time scales (over the past 500-2000 years) for which archives are generally scarce.

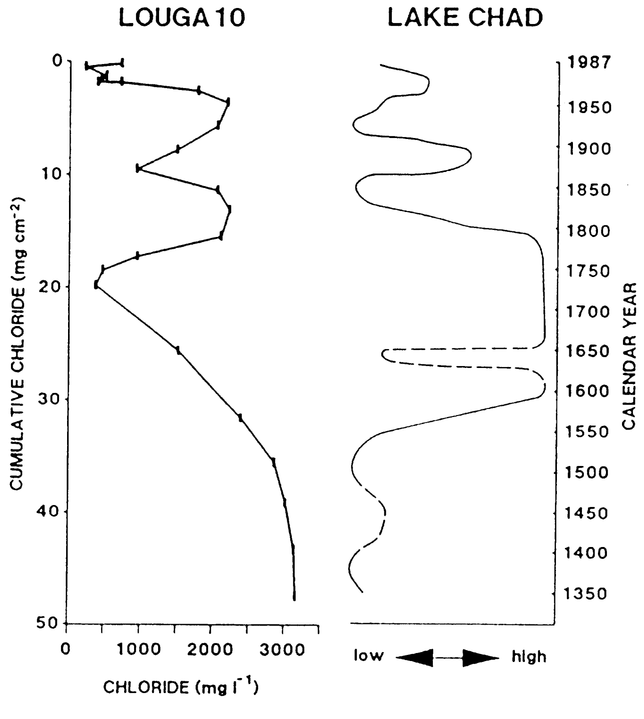

Figure 7. Chloride profile L 10 (near Louga, Senegal) compared with a reconstruction of the water levels of Lake Chad.

A further profile at Louga, northern Senegal (L10) which contains higher chloride concentrations than in the L3 profile is used to attempt an extrapolation beyond the range of instrumentally recorded data (Figure 7). This profile is compared with a reconstruction of water level variations of Lake Chad which is based on sedimentological and palynological data (Maley 1973; Servant and Servant-Vildary 1980). Using the rainfall data (2.8 mg/l) measured over the three year period the profiles have been aligned using a chloride fallout of 1g/m^2/yr since 1950 and of 0.7 g/m^2/yr before 1950, the lower value being arbitrarily chosen to provide a best fit with the Lake Chad record. The data are expressed as cumulative chloride against time where the conversion to years is possible using the values of fallout given above. There is a reasonable correlation between both archives for events at the century scale. Numerical modelling of the profile data show that there is no unique recharge history that can be determined from the profile (Cook et al.1992). However the total recharge that caused the lowering of Cl concentrations above 30,15 and 5mg/cm^2 cumulative chloride (300, 150 and 20 years BP) must have been 150, 50 and 50 mm/yr respectively. Further records are needed from arid and semi-arid regions to strengthen the use of unsaturated zone archives over the longer term, but the L 10 result is consistent with the length of profile which should be preserved using the above model. An unsaturated zone record of 70m has recently been described from southern Niger which represents a recharge history of over 700 yr (Bromley et al 1966).

An unsaturated zone record of 70m has recently been described from southern Niger which represents a recharge history of over 700 yr (Bromley et al 1966). Recharge records over much longer periods representing major climatic shifts have been inferred from the chloride concentrations contained in the unsaturated zone especially in Australia and the southern USA. Allison et al.(1985), Stone (1987) have described profiles up to 28m in South Australia which are thought to contain recharge records up to 30 000 years. Using cumulative chloride vs depth plots they infer that breaks in slope represent changing recharge rates, albeit only within the range 0.07-0.10 mm/yr. Examples of chloride profiles from New Mexico which contain evidence of possible changing climate and recharge over the Holocene are also described by Stone (1987) and some correlation is found with archaeological records. Support for the use of chloride to record climatic/environmental changes at the regional scale over timescales of millennia also comes from work in SW United States by Phillips (1994) who used ^{36}Cl to demonstrate that no by-pass flow occurred and that the piston flow model was valid. The close similarity of all the profiles obtained for the unsaturated zone is interpreted as showing that the soils were hydraulically responding to a regional shift in the soil-surface boundary condition. It is proposed that in particular the records show a response to the major change in the water balance around 13 000 yr BP which is recorded also in the water levels of closed lake basins. Vegetation changes are proposed as one of the most important controls affecting the soil moisture change and hence the water balance and groundwater recharge.

Results from recent studies

Several profiles obtained during the present CRP reported in the country papers as well as in the overview paper (Edmunds and Verhagen 2000) provide further evidence that unsaturated zone profiles can be used universally to measure recharge rates. The general principle applies that where chloride concentrations approach steady state and can be averaged in the unsaturated zone active recharge is occurring with the mean chloride in the profiles being proportional to recharge amount. Stable isotope values may in some cases reflect the Cl enrichment and provide confirmation of evaporative enrichment but unlike Cl cannot be used quantitatively to calculate rates of recharge. In addition however several profiles where piston-type displacement can be inferred may also contain information on the recharge history since oscillations in the Cl profiles are observed.

A simple spread sheet model has been produced which can calibrate the profiles in terms of timescale represented by the chloride stored in the unsaturated zone (cf Cook et al 1992). Cumulative Cl in the profiles is proportional to time and a depositional flux measured in modern rainfall is used to provide the timescale using the moisture contents and chloride in the profiles. Modelling of the recharge history is shown against the best available long term rainfall records for each region. The profiles are shown using the ratio 1/Cl; higher values are therefore indicating wetter years and may be compared directly with the rainfall records. The four examples chosen (from Nigeria, Jordan, Tunisia and Mexico and Nigeria) show a strong contrast in recharge rates.

Magumeri, Nigeria

This site at Magumeri lies on the top of a low line of former dune sands some 40km north of Maiduguri. The mean Cl of the profile is 29.5 mg l^{-1} and using a value of Cl in rain of 1.7 mg l^{-1} a recharge rate of 22.5 mm yr^{-1} calculated (Goni and Edmunds *this volume*). This calculation (in the absence of more reliable data) used rainfall data for Garin Alkali some 250km to the north. A new compilation of the mean annual rainfall for Maiduguri, which is very close to the Magumeri profile site, has been made for the period 1965-1999. The rainfall for this period was 550 mm (as compared with the mean for the period 1915-1999 of 644mm).

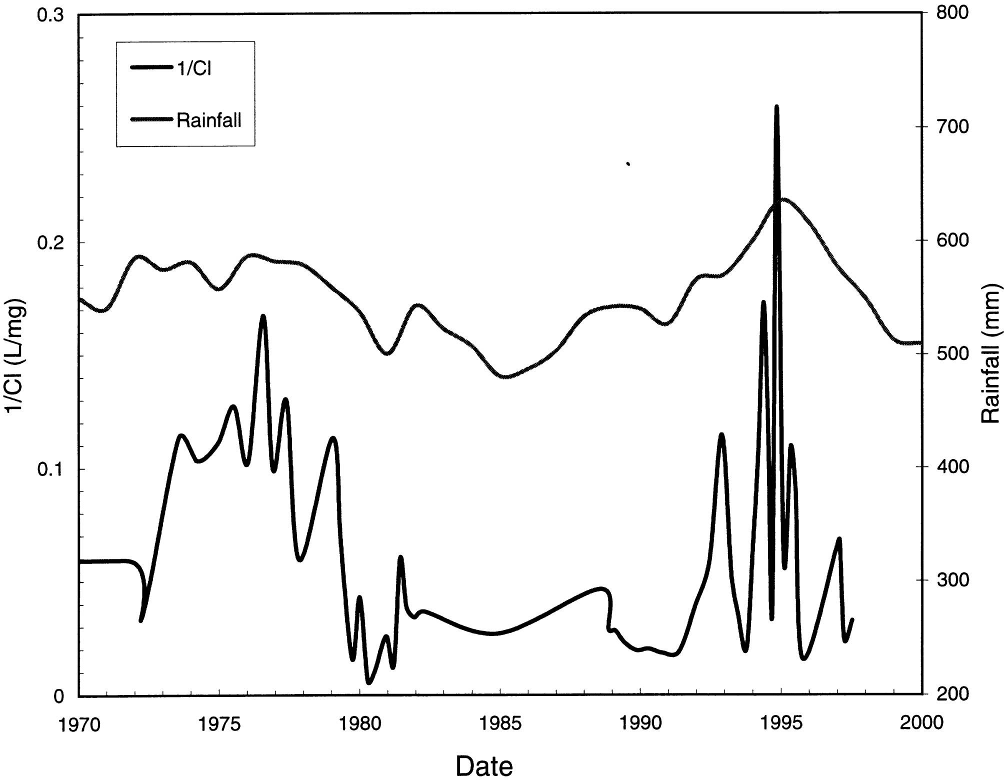

Figure 8. Interstitial water Cl (expressed as 1/Cl) from Magumeri profile, Borno, Nigeria compared with local rainfall over the period 1970-1997.

Using the spread sheet model an excellent match between the Maiduguri (9-year moving average) and the profile Cl (plotted here as 1/Cl) is found (Figure 8). However the mean rainfall chemistry used to produce the matching is 0.7 mg l^{-1} Cl which is lower than for the area near Garin Alkali. This is close to the lower values for Cl obtained at the latter site, but it is noted that the Magumeri site is in an area of higher rainfall and slightly distant from the aid areas. The matching is good even at the 1-3 year scale and this is taken to as an indication of piston flow with only limited dispersion. The profile corresponds to 26 years recharge with a mean recharge rate for this location of 20.7 mg l^{-1}.

Jarash, Jordan

As part of the investigations in Jordan a profile was drilled in the Kurnub sandstones at Jarash in the northern highlands using dry percussion methods. This area has a mean annual rainfall of 480mm. The mean Cl in this 19.5m profile is 173 mg l^{-1} and several peaks and troughs are found (Kilani et al. this volume). Using the current model a mean recharge rate of 36 mm yr^{-1} is calculated, using the local (short term) weighted mean rainfall Cl of 10.2 mg l^{-1}. This value compares with median (unweighted) Cl concentrations in rainfall from Galilee northern Israel of 5.7 mg l^{-1} (Herut et al. 2000). The data have been modelled against the long term records for Jerusalem which date from 1848. The best fit (Figure 9) is obtained if a rainfall Cl value of 7.4 mg l^{-1} is used. This correlation indicates well the lower recharge in the drought years around 1930 as well as in the late 1950's. The lower degree of correlation in the last three decades may relate to land use changes involving higher water use.

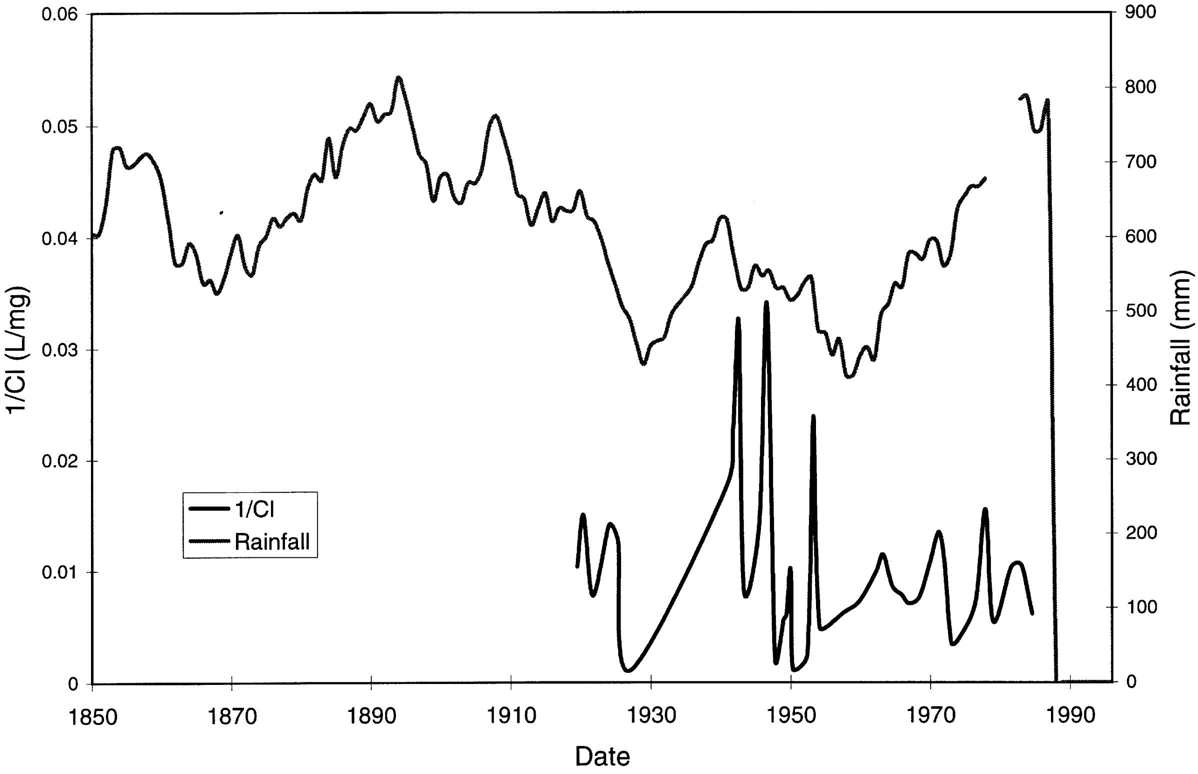

Figure 9. Interstitial water Cl from Jarash, northern Jordan compared with the record of local rainfall (Jerusalem) since 1849.

Tozeur, Tunisia

A series if six profiles have been obtained from the Tozeur area in southern Tunisia both as part of the present project (see Zouari et al this volume) and during a larger study of the groundwater systems of the Grand Erg Orientale (Edmunds et al. 1997). This is an arid region where the mean annual rainfall is 100mm with records available since 1899. The profiles were drilled using a hand augur in semi-consolidated Mio-Pliocene sands covered by natural vegetation. One profile (TOZ 3) drilled to a depth of 19.8m is used to illustrate the results.

The chemistry of rainfall is only available for the coastal site of Sfax over a two year period where the weighted mean was 9 mg l^{-1}. Rainfall records are available for Sfax since 1899 and also for Tunis since 1880. For modelling purposes a rainfall chemistry of 4.7 mg l-1 was arbitrarily chosen on the assumption that the deposition would be lower at the inland site. The plot is shown in Figure 10 where a good correlation is found using the local values, although an even better fit is found for the longer term data if Tunis rainfall (not shown) is used. The profile as calibrated represents a residence time of 781 yrs and a mean recharge over the period of 1.34 mm.

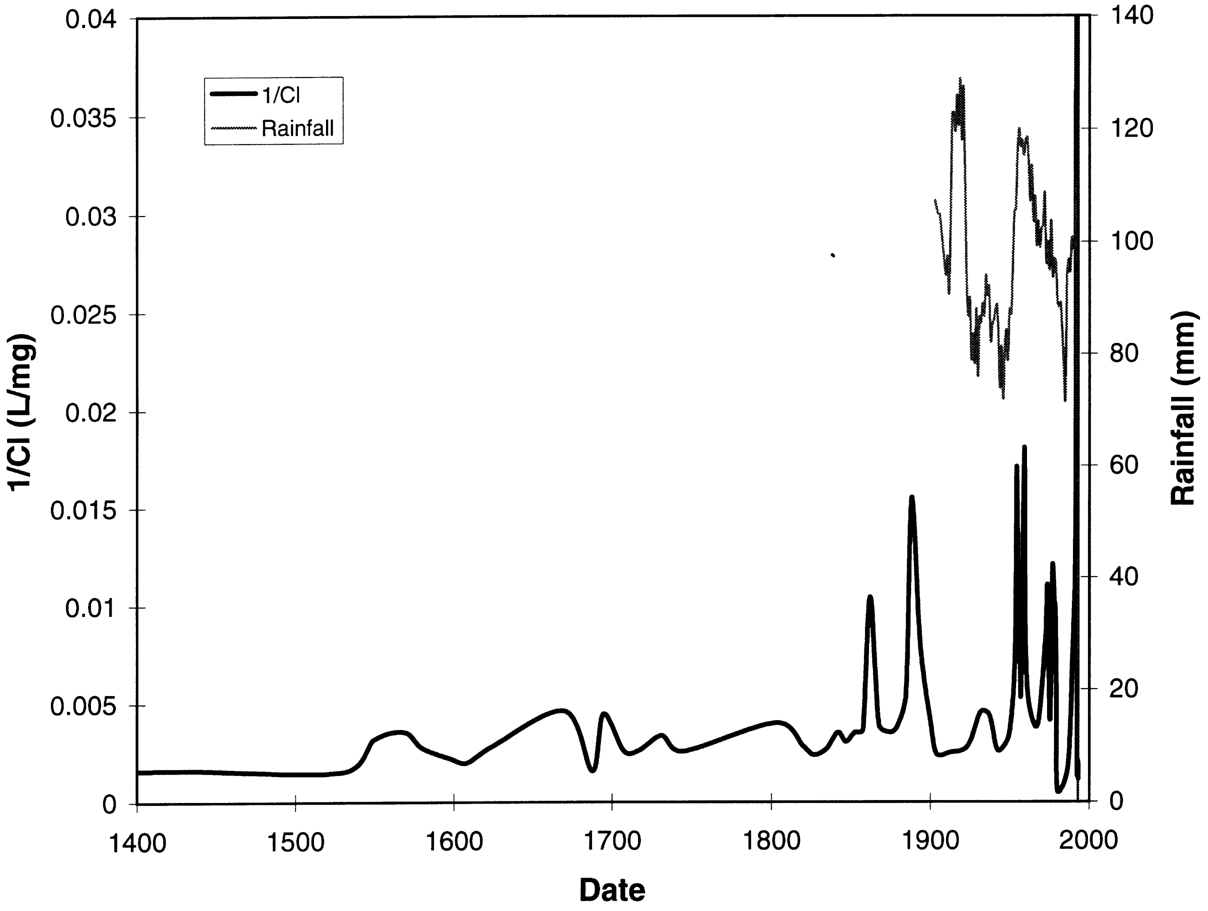

Figure 10. Interstitial Cl from Tozeur 3 borehole, Tunisia, compared with local rainfall since 1849.

These are preliminary results and there is a need especially for longer term measurements of rainfall chemistry and to know its distribution in relation to the synoptic conditions. However it is clear that recharge is occurring, albeit at a low rate, and that a record corresponding to climatic changes over a period of several centuries almost certainly exists.

El Parabien, Mexico

An unsaturated zone profile was drilled in the region of Ciuadad Juarez in Chihuahua, northern Mexico, details of which are given in this volume by Gutierrez-Ojeda. Samples were obtained by dry percussion drilling to a depth of 58m. The region is semi-arid and has a mean annual rainfall of 230mm. The Mesilla Bolson aquifer was drilled in mixed alluvial sediments of Quaternary age with moisture contents ranging from 1 to 27% - near saturation – in some of the clay rich sediments.

Rainfall chemical results are available only for the year of the study. Analyses from samples collected on an event basis ranged from 0.5 to 2.8 mg l^{-1}. Samples collected at a comparable location in New Mexico (Phillips 1994) have a range of Cl concentrations 0.24-0.63 mg l^{-1}. For modelling purposes a value of 0.5 mg l^{-1} is used here. The unsaturated zone chloride concentrations measured at 1 m intervals range from 61 to 4555 mg l^{-1} are used to calculate the average recharge rates and the recharge history.

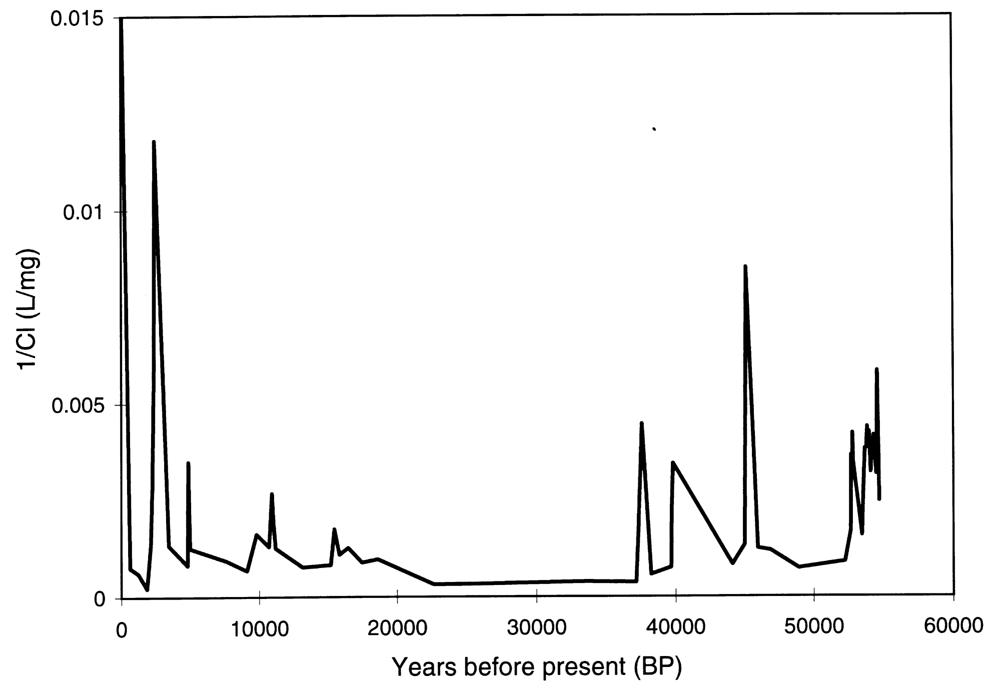

Figure 11. Interstitial water Cl from El Parabien, northern Mexico with model calibration over 50 000 years.

The model results (Figure 11) indicate an average recharge rate of 0.1 mm yr over the whole profile and a residence time for the water stored in the 58m profile of 54.7 k yr using the present day input values . The profile shape and the apparent steady-state indicates that very low recharge rates have been occurring here during the Holocene and late Pleistocene. The mean value of Cl in the lower profile (295 mg l^{-1}) would indicate a higher point source recharge rate of 0.5 mm yr^{-1} for the same input conditions. The profile yet needs much more detailed analysis but it may be provisionally interpreted as a record of changing wetter and drier periods in the late Pleistocene and Holocene with drier conditions being inferred during the late Pleistocene and glacial maximum as compared with the modern era or that prior to 40k yr. Other interpretations would however be possible if the input conditions were to be changed. This is nevertheless a further deep profile from N America which may be compared for example with that from Nevada (Tyler et al 1996) where up to 200k yr record is thought to be available.

Conclusions

A review of studies where isotopic and geochemical techniques have been applied to recharge estimation in the unsaturated zone indicates the value of an integrated approach. Tritium used in Cyprus Senegal and elsewhere provides striking evidence by means of well-preserved tritium peaks that piston flow occurs in many porous media in arid areas. This has in turn provided confidence in the application of Cl mass-balance methods – a much cheaper and more easily accessible method for recharge studies over much wider areas. Point source estimations of recharge can be used together with water table information to determine spatial variability. Stable isotopes ($\delta^{18}O$, $\delta^{2}H$) provide evidence of the extent of evaporative enrichment and hence qualitative indications of recharge, although quantitative estimates are not possible.

It is shown using examples from Senegal that good correlation between the oscillations in Cl and past climate, as expressed in rainfall and river flow records, may be found over the past few centuries. Modelling of results obtained during the CRP from Nigeria, Tunisia, Jordan, Mexico show that, using local rainfall data and chemical inputs from modern rain, a reasonable correlation is found over the time span (ca150yr) of the instrumental records available. By extrapolation, longer term records may also reflect century to millennium scale changes (eg in Mexico) and these longer records tie in with results becoming available from North America.

ACKNOWLEDGMENTS

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Aquifer recharge estimation at the Mesilla Bolson and Guaymas aquifer systems, Mexico

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Abstract. Three unsaturated profiles were obtained from Mesilla Bolson and Guaymas aquifer systems, northern Mexico. About 500 mL of undisturbed soil from depths between 1 m and 58 m below the surface were obtained every meter by dry percussion from a borehole located near Cd Juárez, Chihuahua state. The other two boreholes were located in the southwestern portion of Sonora state; about 500 mL of undisturbed soil from depths 0-5.50 and 0-8.50 m were obtained every 0.25 m by dry drilling at Narciso Mendoza and Guaymas sites, respectively. Samples were contained in sealed glass jars and analyzed for moisture content, chloride, deuterium and nitrate (NO_3-N). The interstitial water was extracted by elution; chloride and nitrate were determined by automated colorimetry while deuterium by direct reduction. Considering an average precipitation at Mesilla Bolson area of 230 mm/year, a chloride rain content of 1 mg/L and a mean Cl content on the unsaturated profile of 977 mg/L below the zero flux plane, we estimated by the Cl mass balance approach a net palaeorecharge in the area of about 0.24 mm/year with a probable time scale profile of 11,000 years. For the Guaymas area the net recharge is in the range 0.11-0.16 mm/year, assuming an average rainfall of 320 mm/year, Cl rainfall content of 3.4 mg/L and mean Cl concentrations on the profiles of 6,939 and 9,470 mg/L below the zero flux plane, respectively.

1. Introduction

During the last decades the use of groundwater has played a vital role on the socioeconomic development of the semiarid and arid areas of Mexico, especially in the northern part of the country where most of the industrial and urban areas relies only on the subsurface water resources.

The water tables around the major development areas of the north have been falling sharply as a result of the present scale of exploitation of groundwater recharged under more favorable climatic conditions, which amounts to the mining of the reserves. This has also resulted in the overexploitation of 97 out of 647 known aquifers of Mexico, which are mostly located in the northeastern, northern and central states of the country. It is an urgent matter to improve understanding of the origins of this groundwater, in particular whether it is being replenished.

Significant recharge at the regional scale in areas with mean annual rainfall below 250 mm/year is usually considered to be unlikely. However in areas with sandy soils and where rainfall intensity is favorable, infiltration may occur even in arid areas on an irregular basis.

Classical methods of recharge estimation based on physical methods are inappropriate in semi-arid/arid regions [1–4] because they have serious limitations. For example, the water balance approach relies on the small difference between rainfall and evaporation, two large numbers, to estimate the recharge. However, the measurement of these two processes has a lot of uncertainty.

The unsaturated zone under favorable conditions may have an important archive of information about water and solute movement, especially in Recent and Quaternary formations.

The isotopic composition and chemical constituents of water infiltrating through the unsaturated zone into the groundwater can be employed to determine the recharge, and contaminant behavior. For example, tritium profiles have been used in the semiarid and arid zones of Australia [5], India [6], Saudi Arabia [7] and Cyprus [8]. The radioactive isotopes ^{36}Cl and ^{3}H, released into the environment during the nuclear weapon tests of the late fifties and early sixties, are useful to investigate the water and solute movement in desert soils. The solute profile approach has been applied in Australia [9-11], Cyprus [8] and Senegal [12] to study the long term recharge, recharge history and water rock interaction.

The objective of this project was to develop an adequate methodology for the accurate determination of the sustainable replenishment of aquifers located in the arid and semiarid regions of northern Mexico and to estimate the long term recharge in pilot arid areas of northern Mexico.

This report presents the results obtained during the three year project duration by the Mexican mission: A description of the study areas, sampling (soil and rain water), analytical determinations (moisture content, chloride, deuterium and nitrate), experimental data and estimation of the recharge. The Mesilla Bolson (Conejos-Médanos) and the Guaymas aquifer systems, northern Mexico, were selected as pilot areas to estimate the recharge by mean of the unsaturated zone profile technique.

Overall the proposed three year programme was designed to contribute to the basic understanding of the fragile groundwater resources in northern Mexico so that informed decisions may be made for the sustainability and long-term management of groundwater on the region.

This project was part of the IAEA Coordinated Research Programme "Isotope based assessment of groundwater renewal and anthropogenic effects in water scarce areas", project CRP 3.30.08.

2. Mesilla Bolson

2.1. Description of the study area

The study area is located in the vicinity of El Parabien ranch, at 40 km to the W of Cd Juárez and in the intersection of parallel 31°35’ N-latitude and meridian 106°52’ W-longitude (Figure 1). The ranch forms part of the Mesilla Bolson aquifer, which is located in the northern Mexican State of Chihuahua. Mean land surface elevation of Mesilla is 1,200 meters above sea level (masl). The area belongs to the Rio Bravo basin and it does not present natural channels or surficial water bodies within the Bolson.

According to the Köppen classification, the Mesilla Bolson has a dry climate, with maximum temperature in the summer of 38°C, minimum of –12°C in the winter and average of 17°C. The mean annual precipitation in the area is 230 mm and the rainy season is from July to September. Evaporation is high with a mean annual value reaching 2,400 mm.

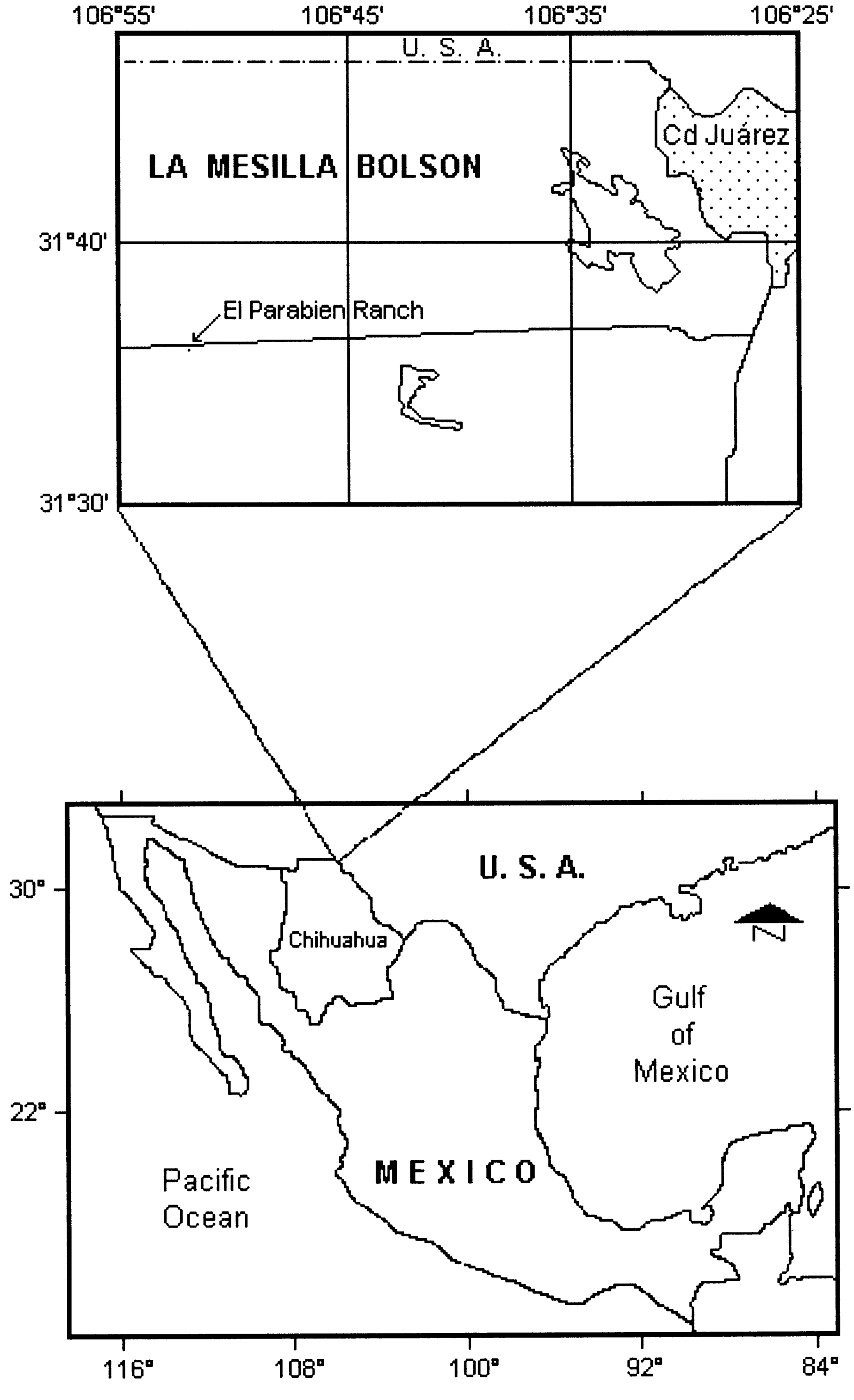

Figure 1. Location of Mesilla Bolson aquifer system.

The Bolson is located in the Basin and Range physiographic province [13] which is characterized by a major anticlinorium with Mesozoic limestones and Jurassic quartzites forming elongated ranges with a NW-SE trend [14]. The elongated limestone ranges have altitudes of 1,700 masl, topographically 550 m above the extensive intermountains valleys called Bolsons. The topography of the valleys is very smooth. The alluvial material filling the Bolsons consists mainly of clay and sand up to 800 m thick, and is overlaid by lacustrine clay deposits. The surface material is made up of Elias sand, in dunes up to 100 m thick, over which grows vegetation typical of semiarid areas: mesquites, palms, etc. The dunes are extensively distributed over the whole area.

The Mesilla Bolson aquifer is unconfined type, covers a total area of about 350 km^2 and is composed of alluvial deposits derived from the erosion of the intrusive and limestone rocks of the surrounding mountains. Winds reworked part of the surficial sediments forming the eolian deposits (dunes). The stratigraphic log of a well (300 m depth) located at 15 m of the drilling site indicates the predominance of fine sand with some clay and silt, and a thin layer of caliche (15-20 cm) at 1-3 m depth.

There are 23 shallow wells in the Bolson with depths lesser than 150 m; they are mainly used to cover the domestic and livestock requirements of the rural communities. In generally, their extraction rates are less than 1 L/s. Thus, the aquifer is still in natural conditions, but it has been considered the next water supply for Cd Juárez. The city has a population of one million people with a required water supply of more than 4 m^3/s. In 1988 the Secretaría de Recursos Hidráulicos (SRH), Water Resources Department, drilled 6 deep wells in order to explore the aquifer potential. The exploration wells reached 300 m depth.

Depth to the water table range from 50 to 90 m; total thickness of the unsaturated zone is about 60-70 m in the vicinity of El Parabien ranch (Figure 2).

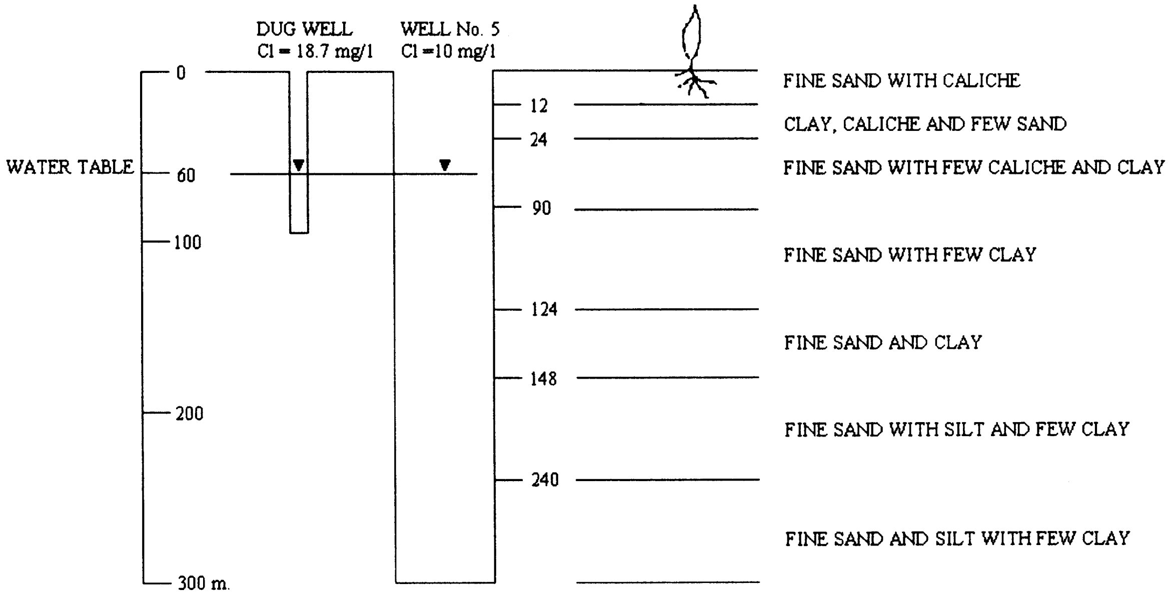

Figure 2. Schematic representation of the Parabien dug well and well No 5.

Groundwater has a predominant NE-SW flow direction. There is also a subsurface flow coming from the USA at the NW. The recharge area is located at the SW and the natural discharge of the aquifer is towards the Rio Bravo. The principal source of recharge is the locally infiltrated rainwater.

A summary of the hydrologic parameters of Mesilla Bolson aquifer system is shown in the next Table 1:

Table 1. Hydrogeologic parameters at Mesilla Bolson

Parameter	Representative value
Hydraulic gradient	0.0005 - 0.001
Transmissivity	2.0 x10^{-3} m^2/s
Hydraulic conductivity	8.69 x 10^{-6} m/s
Effective porosity	0.09

The hydraulic gradient values reflect the slow groundwater movement in the area; transmissivity was estimated in the first 230 m of saturated thickness.

Total Dissolved Solids (TDS) range from 500 to 1,000 mg/L with an area distribution consistent with the principal flow direction. Groundwater is HCO_3 -Ca and SO_4 -Na types and in general its quality is good for human consumption. The low Cl content (10-19 mg/L) suggest that groundwater originates from recent infiltrated rain water. The chloride content at the Parabien dug well is 18.7 mg/L; this shallow groundwater sample was taken the 1st of November of 1996.

2.2. Sampling

2.2.1. Soil

A well was drilled in Mesilla Bolson, Chihuahua from January to June of 1997. The drilling equipment was a Longyear model 34 and the drilling technique was rotary for augering (2" of diameter) and dry percussion for soil sampling (split barrel of 2 1/2" id with sample retainer). Steel casing was necessary for side wall support. About 500 mL of undisturbed soil from depths between 1 m and 58 m below the surface were obtained every meter. Samples 9, 10, 12, 25, 27, 30, 33, 34, 35 and 37 were duplicated, while the interval 42-44 m depth were not sampled. This finally resulted in sixty four samples, which were immediately contained in sealed (with paraffin) glass jars to avoid moisture evaporation. The low moisture, null cementation and low compaction of the soil conditions originated great instability to the side walls of the borehole, which complicated the drive in steel casing and the soil sampling. Samples 1-40 were taken from January to May while samples 41-58 during the first week of June. According to the driller, samples from June were taken under excellent drilling conditions. We suspected an irregular procedure on samples 41-58. We finally decided to perform analysis to the whole set of samples.

2.2.2. Rain water

In august 1996 two rainfall sampling stations were installed (Tenite® Rain Gauge No 110672), Parabien station at 500 m of the drilling site and Cuarentenario station at 30 km from it. Local people collected samples. Fifty four and twenty rain samples from Parabien and Cuarentenario stations were collected, respectively

2.3. Analytical determinations

2.3.1. Soil

The sixty four soil samples were sent in June 1997 to the British Geological Survey (BGS) laboratory in Wallingford, UK, for analysis of Moisture Content, Cl, NO_3-N and δ^2H. CRP-funds were used to cover the corresponding costs.

2.3.1.1. Moisture content

One hundred grams of sample was heated at 70-80°C for 48 hours. The sample was then reweighted and moisture content determined as follows:

$$MC = \left[\frac{(P+W)-(P+D)}{(P+D)-P} \right] x100$$

where:

MC	moisture content (%)
P+W	wet weight of the sand plus beaker
P+D	dry weight of the sand plus beaker
P	weight of the beaker

2.3.1.2. Chloride and nitrate analysis

Fifty grams of the sample to be elutriated was weighed into a beaker, which had previously been washed and rinsed with deionised water. A 30 mL aliquot of deionised water was then added and after being thoroughly stirred, the sample was left for an hour. The supernatant solution was then decanted and filtered (0.45 μm) prior to analysis by automated colorimetry. Chloride and nitrate concentrations were then calculated using the following equation:

$$C = ((MC/(100/S)) + W/(MC/(100/S))) \text{ x elu}$$

where:

C	concentration of the anion in the interstitial water
MC	wet weight moisture content (%)
S	weight of sand (g)
W	volume of deionised water (mL)
elu	concentration of elutriate (mg/L)

2.3.1.3. Isotopic Analysis

Deuterium was analyzed using the direct reduction method [15]. The amount of sand holding 10 :L of water was calculated for each sample on the basis of the dry weight moisture content.

This amount was inserted into a deuterium finger vessel with about 1g of zinc shot at the base and a plug of glass wool approximately half way up. The sand rested on the glass wool to prevent the full effects of reaction heat (500°C) on the minerals and organic compounds in the sand. The reaction tubes were frozen in liquid nitrogen, evacuated and reacted in a hot block for one hour.

After cooling, the vessels were attached to a VG Optima Mass Spectrometer with an automatic inlet manifold for analysis [16,17]. Results are reported relative to V-SMOW. Analytical precision varies with the original moisture content of the sample.

2.3.2. Rain

Seventy four rain samples were collected by local people. Analytical determinations were performed in local laboratories. Rain samples 1-19 from Parabien and 1–20 from Cuarentenario were analyzed in the laboratory of Junta Municipal de Aguas y Saneamiento (JMAS) of Ciudad Juárez, Chihuahua; samples 19-55 in the laboratory of El Paso Texas. After one year of operation, the Cuarentenario station was closed down due to logistic problems. The 1–19 rain chloride concentrations at the Parabien station range from less than 0.5 to 29.8 mg/L. The initial high values were attributed to rain water evaporation and to the high detection limit (5 mg/L) of the analytical technique applied by JMAS. That was the main reason to change of laboratory and to insist with the local people to collect the rain samples immediately after a rain event. The Cl concentrations of rain samples 20–54 range from 0.5 to 2.8 mg/L. Published data about rain Cl content in the New Mexico area [3, 18–21] range from 0.24 to 0.63 mg/L, so the Cl concentrations at El Parabien ranch should range from less than 0.5 to 2.8 mg/L. The analytical techniques used by the JMAS and El Paso laboratories were Argentometric (detection limit of 5.0 mg/L) and Ion Chromatography Method (detection limit of 0.5 mg/L).

2.4. Rain isotopic data from Chihuahua (IAEA) station

The rain isotopic data from GNIP-Chihuahua station (7622500) were taken as input data for Mesilla Bolson and Guaymas aquifer systems. The station is located 400 km south of Cd Juárez, at 28.63° N and 106.07° W, with an altitude of 1,423 mamsl. The 125 pair of δ^2H and δ^{18}O data from the period 1962–1988 were used to obtain the Local Meteoric Water Line (LMWL):

$$\delta^2\mathrm{H} = 7.13 \cdot \delta^{18}\mathrm{O} + 2.78 \quad (r^2 = 0.937,\ n = 125)$$

which were compared with the Global Meteoric Water Line (GMWL):

$$\delta^2\mathrm{H} = 8 \cdot \delta^{18}\mathrm{O} + 10 \quad (\mathrm{VSMOW})$$

2.5. Evaluation

The lithological characteristics of the soil profile extracted from the sixty-four samples is as follows (Table 2): The sediments of this profile are rather heterogeneous as shown from the geological details and display a wide range of moisture contents: sandy horizons have 2–4% moisture, but clay-rich horizons contain up to 15–20% (Table 3). The δ^2H data show some evidence of the typical isotopic enrichment encountered close to the surface in arid zone profiles (Figure 3). Below this, a local peak in δ^2H at 8–9 m may be related to the presence of clay minerals, though such an effect is not apparent further down the profile where clays are present. A steady state of around -60λ extends from approximately 10 m to 35 m below the surface. Below this, there is a fairly abrupt change to a composition with more ‘noise’ but averaging around -35λ. This coincides with consistently low moisture content and chloride concentration.

Table 2. Lithological characteristics of the soil profile

Depth (m)	Description
1	Unconsolidated powdery sand. Mainly very fine to fine grained. Light brown colour.
2–4	Unconsolidated powdery sand. Very fine to fine grained. Small grit sized particles within main matrix. Very light beige colour.
5	Unconsolidated sand. Grain size range from very fine to very coarse including small pebbles. Grains are individually multi-coloured but overall grey brown colour. Mica flakes present.
6–8	Unconsolidated powdery sand. Very fine to fine grained. Very light beige colour.
8–9	Light "chocolate" brown mudstone / clay, semi-consolidated, non-indurated sediment.
10–11	Unconsolidated powdery sand. Very fine to fine grained. Very light beige colour.
12–13	Light "chocolate" brown mudstone / clay, semi-consolidated, non-indurated sediment.
14–18	Unconsolidated powdery sand. Very fine to fine grained. Very light beige colour.
19	Light "chocolate" brown mudstone / clay, semi-consolidated, non-indurated sediment.
20–22	Unconsolidated powdery sand. Very fine to fine grained. Very light beige colour.
23–27	Light brown, semi-consolidated, non-indurated sediment.
28–30	Unconsolidated powdery sand. Very fine to fine grained. Small grit sized particles within main matrix. Very light beige colour.
30	Light "chocolate" brown mudstone / clay, semi-consolidated, non-indurated sediment.
31–32	Unconsolidated, loose, fine to medium grained sand. Dark beige colour due to occurrence of black sand grains.
33–37	Light "chocolate" brown mudstone / clay, semi-consolidated, non-indurated sediment.
38–47	Unconsolidated, loose, fine to medium grained sand. Dark beige colour due to occurrence of black sand grains.
48–58	Unconsolidated sand, well-sorted, mainly medium to coarse grained. Light brown colour with slight reddish tinge.

Table 3. Analytical results of Mesilla Bolson, Chihuahua

Depth (m)	M.C. (%)	Cl (mg/L)	NO_3-N (mg/L)	δ^2H (‰)
1.0	3.31	61.09	6.35	-61
2.0	3.49	1333.06	< 0.1	-71
3.0	2.74	1664.10	< 0.1	-69
4.0	1.06	4555.76	< 0.1	-65
5.0	2.94	743.98	< 0.1	-56
6.0	2.06	368.56	< 0.1	-54
7.0	5.24	177.37	0.44	-51
8.0	8.22	84.67	0.12	-52

Table 3. (cont.)

Depth (m)	M.C. (%)	Cl (mg/L)	NO_3-N (mg/L)	δ^2H (‰)
9.0	10.01	756.64	1.78	-56
9.0	17.02	1230.83	< 0.1	-62
10.0	2.60	287.27	1.95	-63
10.0	2.35	459.41	2.52	-64
11.0	1.27	802.31	< 0.1	-62
12.0	18.64	1079.87	0.40	-63
12.0	15.40	1485.31	2.89	-62
13.0	17.36	619.54	< 0.1	-60
14.0	8.87	774.28	3.71	-60
15.0	4.39	375.23	< 0.1	-63
16.0	1.77	519.69	< 0.1	-58
17.0	1.37	798.61	< 0.1	-60
18.0	11.45	1317.27	0.79	-60
19.0	12.70	1227.39	1.75	-61
20.0	3.51	574.07	< 0.1	-65
21.0	1.83	681.24	< 0.1	-56
22.0	1.74	920.13	< 0.1	-58
23.0	6.13	796.24	< 0.1	-51
24.0	6.73	1135.94	-	-60
25.0	8.36	1042.68	< 0.1	-56
25.0	19.32	3186.27	5.83	-59
26.0	19.04	3042.56	-	-64
27.0	21.01	2657.83	6.53	-67
27.0	19.25	2781.84	-	-65
28.0	3.64	623.90	< 0.1	-61
29.0	9.54	224.87	< 0.1	-58
30.0	2.81	1783.41	5.35	-62
30.0	16.43	1345.57	2.59	-61
31.0	1.53	431.95	1.67	-58
32.0	2.35	292.60	< 0.1	-55
33.0	27.13	1220.09	-	-66
33.0	18.17	755.58	6.21	-64
34.0	17.22	117.72	10.57	-60
34.0	15.39	809.66	6.49	-61
35.0	16.59	848.73	6.53	-58
35.0	22.32	1390.22	10.35	-63
37.0	15.06	1123.99	8.68	-59
37.0	10.69	598.43	4.95	-59
38.0	1.63	275.76	< 0.1	-50
39.0	1.94	318.78	< 0.1	-51
40.0	1.00	238.29	< 0.1	-46
41.0	0.97	289.71	< 0.1	-49
45.0	1.90	637.21	8.33	-37
46.0	2.93	334.92	3.39	-50
47.0	2.67	263.27	< 0.1	-44
48.0	2.45	263.00	< 0.1	-42
49.0	2.90	229.13	< 0.1	-38
50.0	2.07	247.63	0.98	-37
51.0	2.39	235.94	< 0.1	-42

Table 3. (cont.)

Depth (m)	M.C. (%)	Cl (mg/L)	NO_3-N (mg/L)	δ^2H (‰)
52.0	2.57	313.10	< 0.1	-50
53.0	1.65	261.14	< 0.1	-48
54.0	2.73	253.20	< 0.1	-34
55.0	2.13	241.00	< 0.1	-46
56.0	4.55	317.77	< 0.1	-47
57.0	3.94	171.94	< 0.1	-41
58.0	2.27	407.99	< 0.1	-55

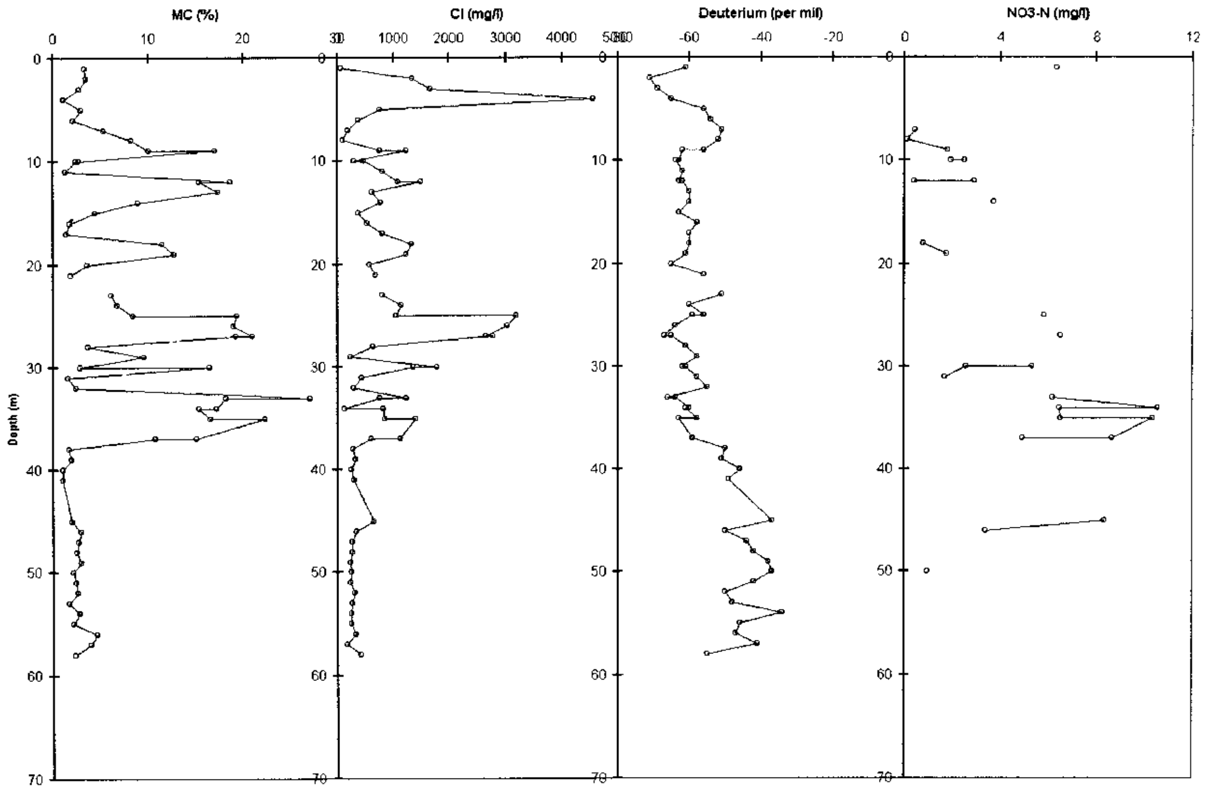

Figure 3. Unsaturated profiles from Mesilla Bolson, Chihuahua State, Mexico.

The chloride profile displays also a typical marked enrichment close to the surface and at 25–27 m below the surface (Figure 3). The latter coincides with a clay-rich horizon containing up to 21% of moisture content. Finally, the NO_3-N data shows no significant trend.

A summary of the analytical results is shown in the following Table 4:

Table 4. Summary of the analytical results from 1 to 58 m depth.

Parameter	Range	Average
MC (%)	0.97 to 27.13	7.63
Cl (mg/L)	61 to 4560	858
δ^2H (‰)	-71 to -34	-56
NO_3-N (mg/L)	0.1 to 10.57	4.28

The evaluation of the recharge rate at Mesilla Bolson aquifer, based on the chloride mass balance and applied to the 8–40 m depth interval (below the zero flux plane and disregarding the 41–58 m noise data), is of 0.24 mm/year considering an average rainfall of 230 mm/year, a value of 1 mg/L of Cl in rainfall and a mean concentration of 977 mg/L in the Cl profile. It is possible that the timescale of the profile represents some 11,000 years. If we consider the whole profile, the estimated recharge in the area would be 0.27 mm/year and the time scale of 17,000 years.

Table 5. Summary of the analytical results from 8 to 40 m depth

Parameter	Unsaturated Zone		Groundwater
	Range	Average	
MC (%)	1.0 to 27.13	10.09	
Cl (mg/L)	85 to 3,190	977	10 to 19
δ^2H (‰)	-67 to -46	-59.5	-65.5 to –49.8 [14]
NO_3-N (mg/L)	0.12 to 10.57	4.36	
^{18}O ($^{o}/_{oo}$)			-7.7 to –4.8 [14]

The average Cl concentration in the unsaturated zone is 2 orders of magnitude higher than the average Cl content found in the groundwater. This could be due to recharge originated in other areas and transported by the regional groundwater flow or to the bypass flow of the locally infiltrated rain water.

From Figure 4, it can be observed an evaporation effect at LMWL with respect to GMWL. The intersection of both lines is at the point (δ^{18}O = -8.32, δ^2H = -56.57), which is close to the local groundwater values. On the other hand, the interstitial water data of δ^2H (Table 5) are in the range –71 to –34 ‰ so we can expect δ^{18}O data in the range of –35 to –10 ‰. Both, the interstitial water and the groundwater data are waters of recent infiltration, geologically speaking.

The estimated recharge and unsaturated profile data of El Parabien ranch are consistent with the published data of El Hueco Bolson, Texas [18–20], located 100 km east of Mesilla Bolson, Chihuahua, where the US Government pretend to install a low radioactive waste disposal site.

In order to determine the concentration peak of ^{3}H in the unsaturated zone of Mesilla Bolson aquifer system and the recharge variability (spatial and temporal) in the area, a hand augering campaign (dry drilling) was performed during the first semester of 1998. In all the tested places the caliche layer appeared at 2–3 m depth which caused to stop the hand drilling. From the 24th of July to the 1st of August of 1998, a new hand drilling process was initiated. The new site was located at about 400 m from the initial one. The first activity was to drill across the caliche layer, which took two full days of work. Dry drilling was very difficult and slow due to the low moisture content of the soil. This also produced high instability on the sidewalls of the hole, so it was necessary to case (PVC) the hole. Soil samples were taken every 0.25 m depth; drilling was stopped after reaching only three meters depth, because the sand auger got fissured due to the very dry soil conditions. Dr Edmunds suggested to look for an alternate area: Mexicali at Baja California state or Guaymas at Sonora state. Several places of Mexicali were also tested during July 1997; drilling was not possible due to the presence of small pebbles on the soil profile and to the extreme dry soil conditions (average rain of 60 mm/year).

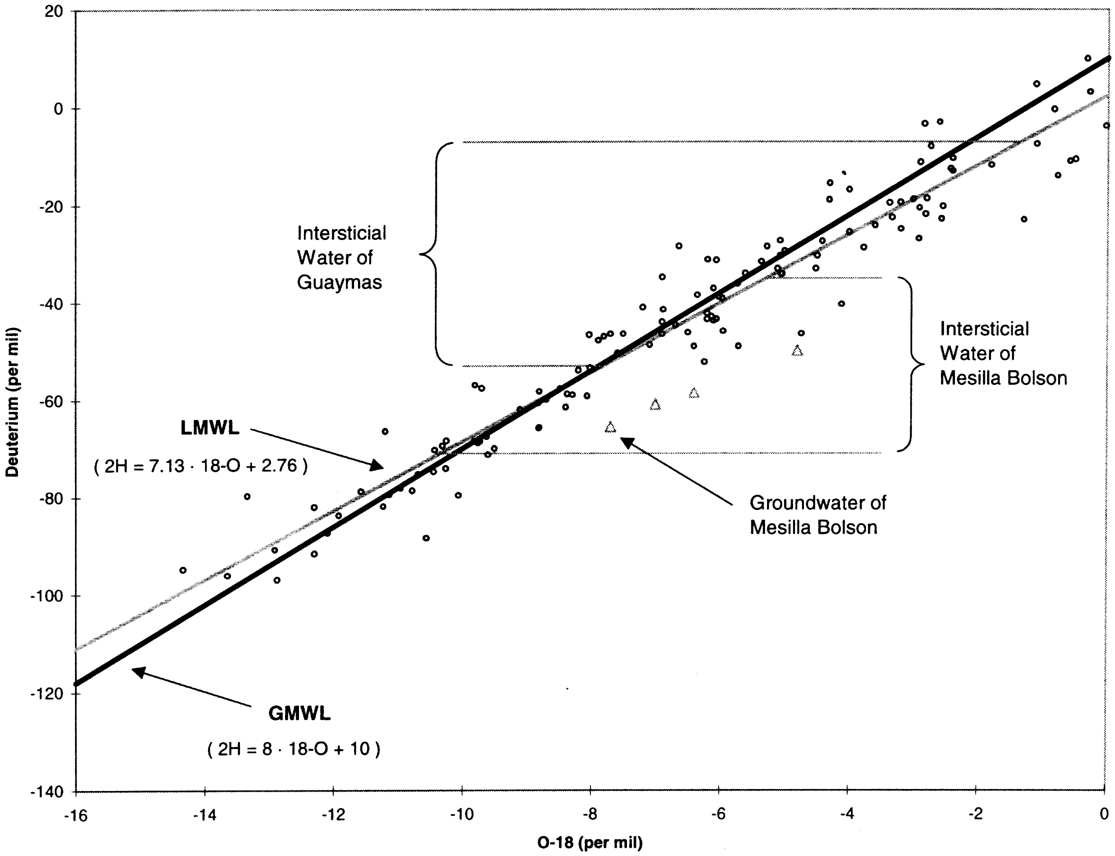

Figure 4. Global and local (Chihuahua IAEA station) meteoric water lines.

Table 6. Comparison of data of Mesilla and Hueco Bolsons

Description	El Hueco Bolson Texas	Mesilla Bolson Chihuahua
Precipitation (mm/year)	280	230
Depth to water table (m)	150	60-65
Caliche layer (m)	1-2	1-3
Cl rain (mg/L)	0.40 to 0.63	0.5 to 2.8
Recharge rate (mm/year)	0.01 to 0.7	0.24
Maximum Cl (g/m^3)	9,300	4,560
Time scale (years)	10,000 to 30,000	11,000
Depth to tritium peaks (m)	0.0, 0.6, 1.4	?

During the drilling process at the new site we observed the presence of roots and small channels or tubes of carbonates below the caliche layer. The water that infiltrates through the caliche layer dissolves the caliche and forms small channels (tubes) through which the water could move faster vertically downgradient. This could explain the bypass flow ($Cl_{gw} < Cl_{uz}$). However, the extreme dry conditions of the soil suggest that water movement through the unsaturated zone is very slow and therefore the results of the chloride profile technique are more realistic for the study area. The low Cl content found in the upper part of the aquifer (Parabien dug well) could be due to a regional groundwater flow from external areas. More information is required to define the recharge mechanisms.

3. Guaymas

3.1. Description of the study area

The study area is located in the semiarid region of the Guaymas Valley. The valley is an important coastal area located in the southwestern portion of the Sonora state, Mexico (Figure 5), between 27°53' and 28°50' latitude N and 110°15' and 111°10' longitude W. The mean elevation of the area is 50 mamsl. The main cities are Guaymas and Empalme, which had a total population of 233,798 inhabitants in 1990.

The Guaymas Valley is part of the lower sub-basin of the Matape River and covers an area of 5,700 km^2 with a north-south trend. The Matape River controls drainage processes within the basin; the river is only active during the rainy season and has an average discharge of 35 Mm^3/year.

The main economic activities are fishing, agriculture, cattle raising, and tourism. Groundwater represents the main source of water for the municipal and agricultural activities of the area. Thirty four percent of the 28,000 ha dedicated to agriculture are subject to irrigation.

The climate of this region is classified as semiarid and it is characterized by high temperature and low precipitation. Temperature ranges from 15°C to 30°C, with an average of 25°C on the period 1966–1986. Mean annual precipitation is 320 mm while potential evaporation rates reach 2,600 mm/year [22]; precipitation events are intense but short-lived and they occur primarily during late summer - early autumn.

The valley is composed of grabens and dikes, trending from north to south, which resulted from tectonic activity over the Tertiary basal deposits of granitic and andesitic rocks of the Cretaceous Period [23]. Quaternary detritus eroded from the adjacent ranges progressively filled the valley.

The Quaternary deposits of the valley provide excellent pathways for deep percolation and recharge. High porosity and permeability characterize the sand alluvial deposits. These sand layers cover the central and upper portion of the aquifer. Their saturated water thickness has been estimated to be 200 m under steady state conditions [24–27]. The piedmont deposits of the northern portion consist mainly of gravel, silt and sand. A thick shale of marine origin called "Blue Clay" separates the regional aquifer into an unconfined and a semi-confined unit [25]. The unconfined unit occurs near the margins of the valley and has a saturated thickness of up to 190 m [27], which increases towards the center of the valley. The confined aquifer extends approximately from Ortiz Levee to Maytorena.

The hydraulic conductivity ranges from 3×10^{-4} to 1.5×10^{-5} m/s for the unconfined unit. The specific yield has been assigned a value of 0.12 [26]. Specific capacities of the wells completed within this unit are between 9 and 100 L/s/m [27]. For the semi-confined unit, the transmissivity values range from 2.2×10^{-3} to 5.0×10^{-3} m^2/s, with a storage coefficient of about 10^{-4}. Mean specific capacity for the semi-confined unit is about 12 L/s/m.

Groundwater flow under natural conditions was from inland towards the coast (north to south); the aquifer was discharging fresh water into the Gulf of California (Figure 6). Heavy groundwater abstraction for agricultural use started in 1950, reversing the natural hydraulic gradient. As a result, seawater intruded the fresh water aquifer deteriorating the groundwater quality and impacting water usage for municipal and industrial activities. Several wells and adjacent farming areas had to be abandoned.

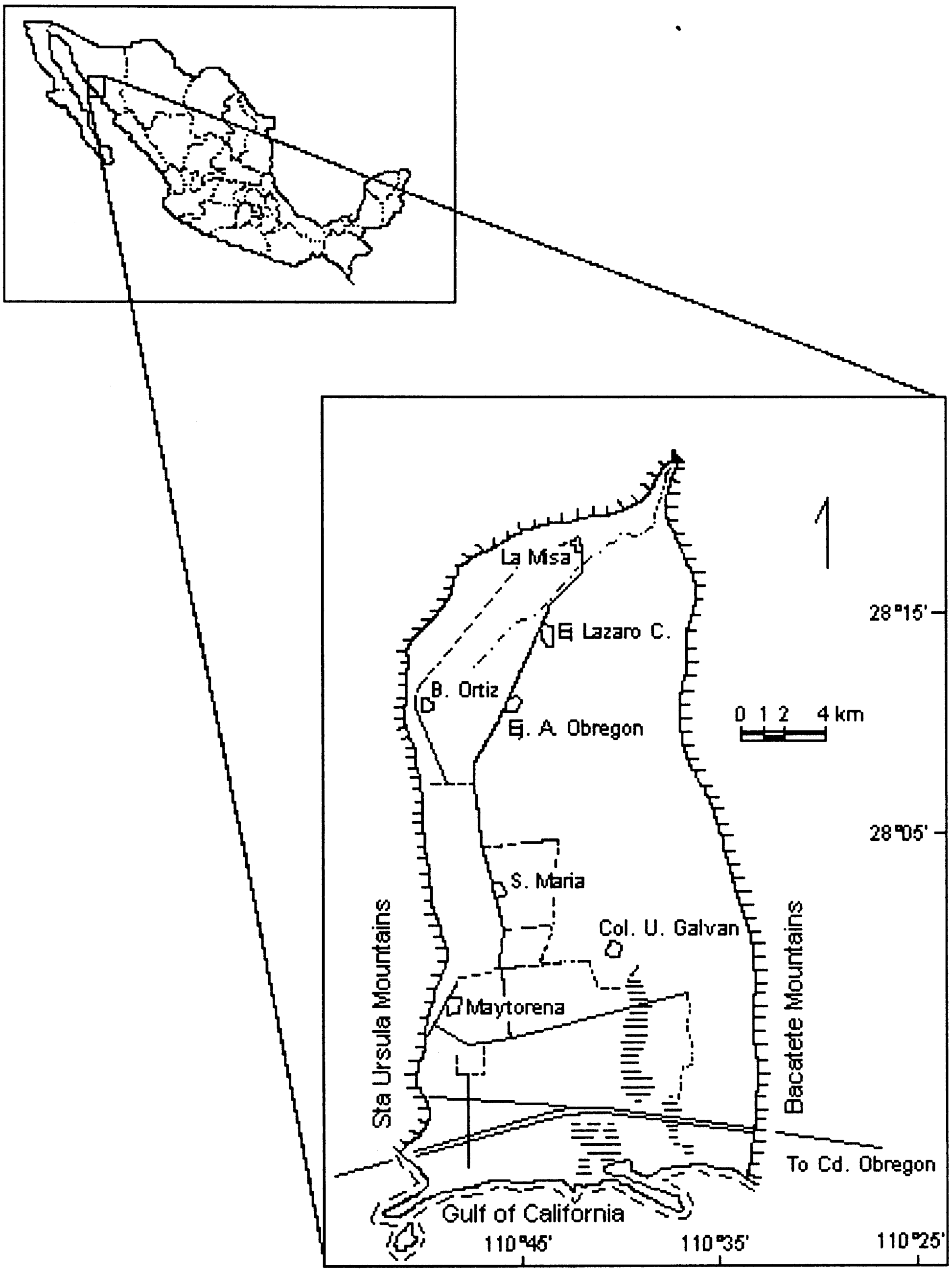

Figure 5. Location of Guaymas aquifer, Sonora state.

Groundwater discharge through the 250 active wells (completed mainly in the unconfined unit) is about 185 Mm^3/year while the estimated natural recharge is of 100 Mm^3/year. Groundwater abstraction reduction has been recommended since 1967 without success [22, 24, 25]. As a result, depth to water table during the 1990–1991 season ranged from 25 to 120 m, with an average of 82 m [28]. Maximum depths were observed near Maytorena town and to the west of Santa Maria de Guaymas. Maximum water table elevation reached 55 meters below mean sea level.

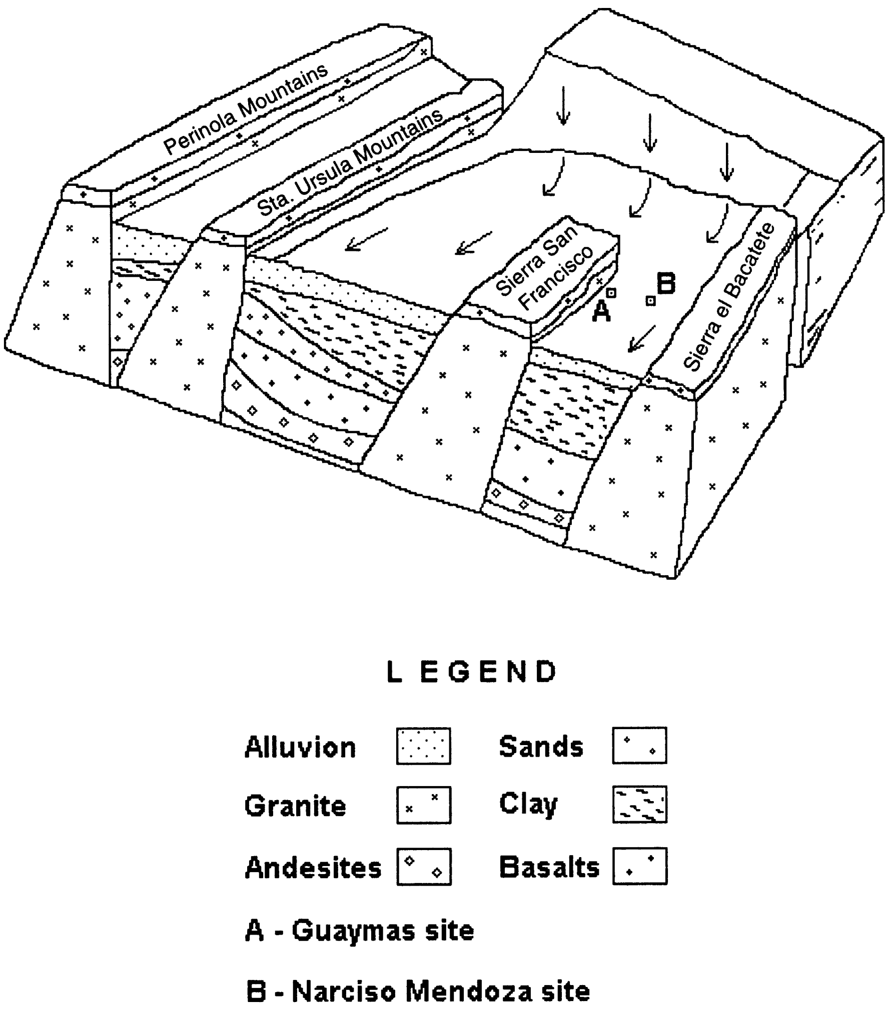

Figure 6. Groundwater flow system under natural conditions at Guaymas aquifer

Recharge at Guaymas aquifer occurs due to different mechanisms: (1) horizontal flow from the Upper Matape Basin, (2) vertical recharge at the alluvial fans of the northern portion of the area, (3) river leakage from the Matape River during the rainy season, and (4) areal discharge over the valley. It is estimated that between 20 and 30% of the irrigation volume becomes deep percolation. An upward component of flow through the "Blue Clay" is thought to contribute with 10 Mm^3 to the water balance of the unconfined aquifer [22].

The water quality of the aquifer has changed as a result of changes in natural groundwater flow. The saline front has reached wells located at 10-12 km from the coastline. TDS values range from 6,000 to 300 ppm. Sodium and chloride concentrations decrease from near the shore towards the center of the valley (1,100 to 460 mg/L for chloride; 529 to 207 mg/L for sodium). Increase in chloride content from background levels (90 mg/L) confirms seawater intrusion in response to heavy pumpage at the Guaymas aquifer. A zone of good water quality is found near the town of Mi Patria es Primero where chloride concentrations are about 71 mg/L.

The groundwater quality at the Cruz de Piedra region, eastern part of the aquifer, experiences a different seawater influence because of the lesser abstraction rates than the western portion of the aquifer.

3.2. Sampling

3.2.1. Soil

Twenty eight geologic samples from the Guaymas Valley were taken by dry drilling from the 9th to the 11th of February of 1999 at two sites: 11 from the Narciso Mendoza site and 17 from the Guaymas site (Table 7). The UTM coordinates of Narciso Mendoza are 545 100 and 3 100 308 while for Guaymas site are 541 806 and 3 098 717 (Figure 5). About 500 mL of undisturbed soil were obtained every 0.25 m. Samples were obtained with a Dormer™ sand auger, transposed to plastic bags from where were immediately contained in sealed (with paraffin) glass jars. Drilling was stopped after reaching 5.50 m depth at Narciso Mendoza site and 8.50 m depth at Guaymas site, due to the presence of hard strata or gravels in the soil profile. At least 4 or 5 sites were tested before the successful drillings described above.

3.3. Analytical determinations

The twenty eight soil samples were sent in March 1999 to the British Geological Survey (BGS) laboratory in Wallingford, UK, for analysis of Moisture Content, Cl, NO_3-N and δ^2H. CRP-funds were used to cover the corresponding costs.

3.4. Evaluation

3.4.1. Narciso Mendoza site

The sediments of the profile consist mainly of quaternary sands. The sands show an increase in the gravel content at the interval 2.25–3.00 m depth and an increase in the clay content at 3.75–4.50 m depth.

The MC values (Table 7) found close to the soil surface show the evaporation effects, while the average MC is of 6.16% (Figure 7). The minimum and maximum values are found at 2.25–3.00 and 3.75–4.50 m depths, which are associated with layers with coarser and finer sediment content, respectively. Below the 3.75–4.50 interval, the MC decreases to average values.

Table 7. Analytical results of Guaymas, Sonora

Top Depth (m)	Bottom Depth (m)	M.C. (%)	Cl (mg/L)	NO_3 (mg/L)	δ^2H (‰)
Guaymas site					
0.25	0.50	3.57	23,972.10	222.11	-13
0.75	1.00	5.95	11,901.92	53.98	-7
1.25	1.50	7.11	6,227.93	20.51	-11
1.75	2.00	10.50	13,124.03	66.39	-15
2.25	2.50	10.92	15,269.98	38.12	-25
2.75	3.00	10.30	11,693.16	20.63	-21
3.25	3.50	10.05	10,112.43	16.04	-29
3.75	4.00	10.99	11,825.38	19.16	-29
4.25	4.50	12.92	12,061.39	21.05	-30

Table 7. (cont.)

Top Depth (m)	Bottom Depth (m)	M.C. (%)	Cl (mg/L)	NO_3 (mg/L)	δ^2H (‰)
4.75	5.00	12.43	13,474.52	22.35	-34
5.25	5.50	9.73	12,713.08	26.43	-26
5.75	6.00	11.78	11,236.58	15.57	-23
6.25	6.50	9.95	5,332.40	9.82	-34
6.75	7.00	8.01	5,922.58	11.80	-36
7.25	7.50	6.11	3,405.73	6.65	-28
7.75	8.00	3.52	3,482.14	15.48	-44
8.25	8.50	2.57	6,170.48	22.67	-53
Narciso Mendoza site					
0.50	0.75	6.55	13,679.26	92.39	-4
0.75	1.00	8.51	8,505.10	38.88	-5
1.25	1.50	7.40	6,491.56	4.86	-12
1.75	2.00	4.65	7,866.41	7.55	-29
2.25	2.50	2.55	7,408.40	7.10	-29
2.75	3.00	3.01	2,376.89	1.10	-27
3.25	3.50	5.28	7,349.56	2.89	-30
3.75	4.00	9.36	9,437.74	1.13	-30
4.25	4.50	8.60	7,289.98	2.31	-27
4.75	5.00	7.28	8,513.07	1.22	-20
5.25	5.50	4.58	5,719.83	2.86	-24

The Cl content depicts a typical marked enrichment close to the surface; below this, there is steady state around 7,300 mg/L with some variations, which include the coarser sediments of the profile where the minimum values are present.

The δ^2H data show the typical isotopic enrichment encountered close to the surface in arid zone profiles. Below this, there is a steady state around –28%, with a local peak at 5.0 m depth.

Nitrate profile shows the elevated values found at the upper soil zone beneath uncultivated areas [29]. Below 2.75 m there is steady state at about 2.10 mg/L.

3.4.2. Guaymas site

The lithology of this profile is as follows: from 0.25 to 6.0 m the sediments are Quaternary sands mainly with a light increase in the finer sediment content at the intervals 1.75-2.50 m and 4.25-5.00 m depth; from 6.0 to 8.50 the sediments show an increase in the gravel content. The moisture content values depict the evaporation effect found at the soil surface (Figure 8). From 1.75 to 6.00 m there is an steady state of around 11%, and form 6.00 to 8.50 the MC experience an decreasing trend up to a minimum of 2.57%, due to the presence of coarser sediments.

The Cl profile displays also a typical marked enrichment close to the surface. From 1.75 to 6.00 m depth, there is a steady state of around 12,000 mg/L. Below this, the Cl profile experience a shift towards a new steady state of around 5,000 mg/L, which is associated with coarser sediments.

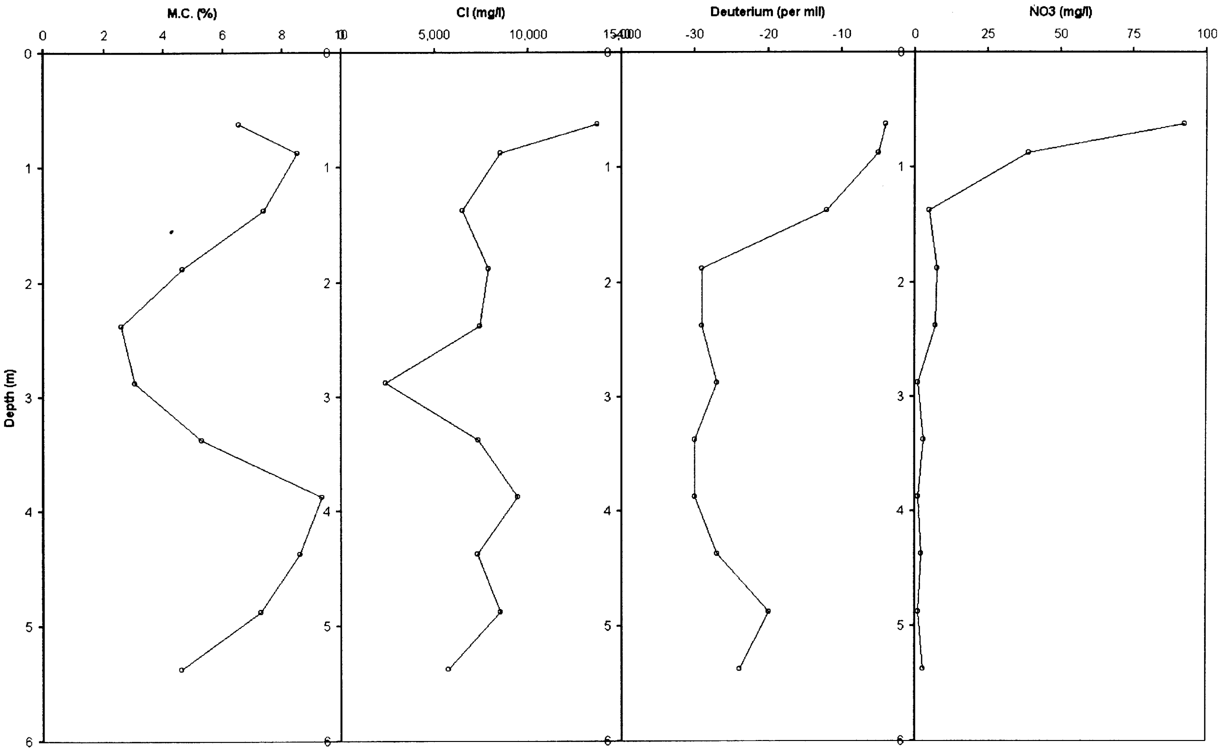

Figure 7. Unsaturated profiles from Guaymas site, Sonora State, Mexico.

The deuterium profile also shows some evidence of the typical isotopic enrichment encountered close to the surface in arid zone profiles (Figure 7). A general depletion tendency is observed along the profile, although it can be observed a quasi steady state from 2.25 to 7.50 m depth at a value of –29%.

Nitrate profile also shows elevated values at the top. At the 1.75 m there is a local peak associated with the finer sediments of this stratum. From 2.75 to 5.50 there is a steady state of around 20 mg/L, and below this, nitrate values show a decreasing trend and finally a content increase before reaching the bottom portion.

A summary of the analytical results is shown in the next Table 8:

Table 8. Summary of the analytical results from Guaymas aquifer

Parameter	Range	Average
	Guaymas site	
MC (%)	2.57 to 12.92	8.61
Cl (mg/L)	3,406 to 23,972	10,466
δ^2H (‰)	-53 to –7	-27
NO_3-N (mg/L)	6.65 to 222.11	35.81
	Narciso Mendoza site	
MC (%)	2.55 to 9.36	6.16
Cl (mg/L)	2,377 to 13,679	7,694
δ^2H (‰)	-30 to –4	-22
NO_3-N (mg/L)	1.10 to 92.39	14.75

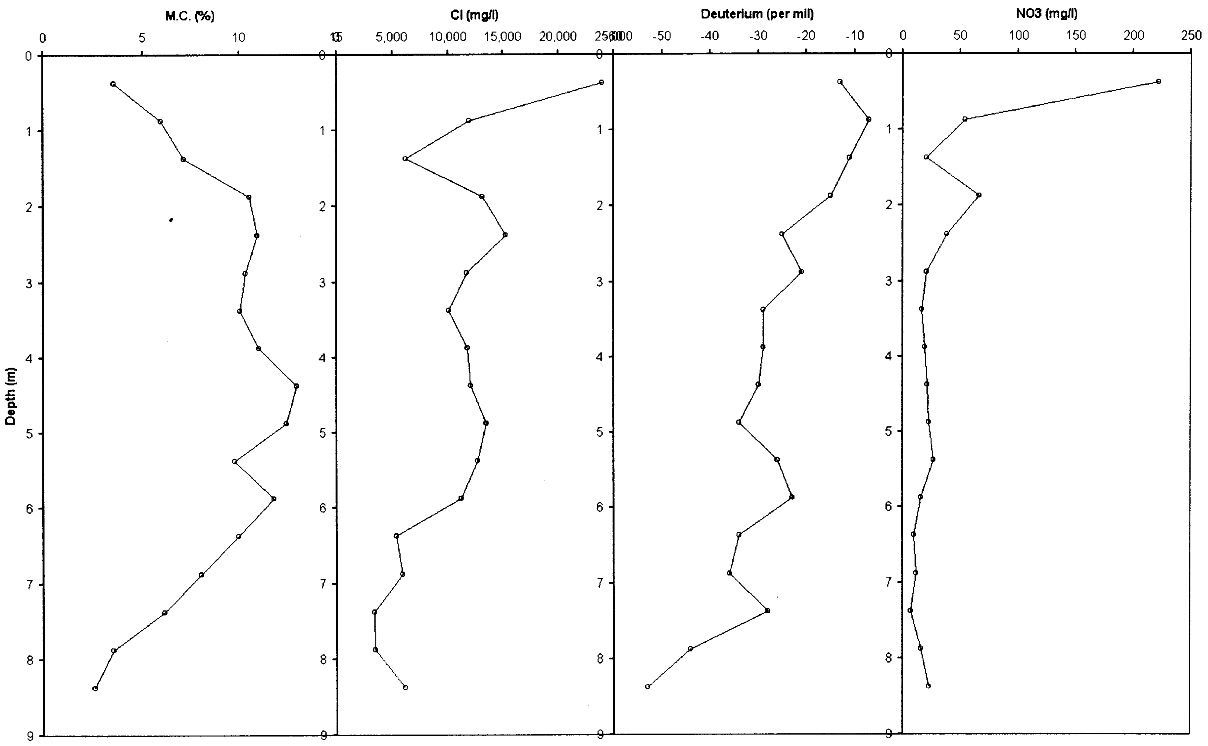

Figure 8. Unsaturated profiles from Narciso Mendoza site, Sonora State, Mexico.

A rain analysis performed by the Instituto Tecnológico de Sonora showed a Cl rain content in the area of 3.47 mg/L. According to Ref. [21], the Cl rain concentration in the coastal areas of California, USA, is about 3.31 mg/L. More rain samples need to be obtained in this area in order to corroborate the Cl content in the rain.

Recharge rate evaluation at Narciso Mendoza and Guaymas sites, based on the chloride mass balance and applied to the 1.25-5.50 and 1.25–8.50 m depth intervals, are of 0.16 and 0.11 mm/year, respectively. The latter assumes an average rainfall of 320 mm/year, a value of 3.4 mg/L of Cl in rainfall and mean Cl concentrations on the profiles of 6,939 and 9,470 mg/L below the zero flux plane (1.25 m depth), respectively.

The Cl concentrations in the unsaturated zones are considerable higher than those found at the groundwater. This means that the areal recharge over the valley is insignificant compared with other recharge mechanisms: horizontal flow, alluvial fans and river leakage. The estimated recharge values represent 0.04-0.05% of the total rain.

The lower part of the Guaymas site profiles experience a MC and Cl content decrease, deuterium depletion and a nitrate content increase which could be due to a different recharge mechanism. The site is located at less than 1 km from the San Francisquito hills. During the drilling process we reached a hard stratum that represents the contact between the hard rock and the Quaternary sediments. This contact layer could represent a preferential path for water infiltrated at the hill or in the alluvial fan. That could explain the relative lower Cl content, higher nitrate concentrations and the depletion of deuterium.

No information about the groundwater isotopic content was available. The interstitial water data of δ^2H (Table 7) on both sites are in the range –53 to –7 ‰ so we can expect δ^{18}O data in the range of –8 to –1 ‰ (Figure 4).

4. Publication

The results of the first year project activities were orally presented at the XXIII General Assembly of the European Geophysical Society, celebrated at Nice France from 20-24 of April, 1998 (Session HSA6 Hydrology and soil processes .1 Recent advances in tracers in vadose zone hydrology: Tuesday 21 April 1998). The title of the presentation was "Recharge Estimation at the Conejos-Medanos aquifer system, Northern Mexico".

5. Conclusions and recomendations

The recharge rate at Mesilla Bolson aquifer systems is about 0.24 mm/year; Future aquifer exploitation should be based on the non renewable water resources.

For the Guaymas aquifer system estimated recharge values represent 0.04-0.05% of the total rain which means that the areal recharge over the valley is insignificant compared with other recharge mechanisms.

More information about the chemical and isotopic content of the unsaturated zone and the groundwater in both studied areas is required in order to discern about the groundwater recharge mechanisms and the spatial variability of the areal recharge.

It is recommended to continue the chemical determination of rainfall in the area, in order to know the input values of the recharge for the regional aquifers.

The solute profile technique is potentially important for investigating the unsaturated zones of arid and semiarid regions of northern Mexico, and for estimating recharge of aquifers of northern Mexico, providing input data for chloride is available (Edmunds *et al.*, 1988).

ACKNOWLEDGEMENTS

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Isotope studies of a thick unsaturated zone in a semi-arid area of Southern Africa

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ABSTRACT

Unsaturated zone profiles ranging in depth from 8 m to 22 m were obtained by hand augering an aeolian sand cover in the southern reaches of the semi-arid Kalahari thirstland. Moisture contents were rather low (< 3 wt.%); in situ moisture chloride concentrations, measured by selective ion electrode following elutriation, are generally < 500 ppm. Deuterium in the moisture was measured mass spectrometrically by direct quantitative conversion to hydrogen on zinc metal of moist soil samples. A novel technique of direct equilibration was developed for oxygen-18 analysis. Neither a thermonuclear tritium peak nor a stable isotope evaporation inversion near the surface could be observed in any of the profiles. Remarkable differences both laterally and vertically are observed in most parameters measured between profiles taken a few tens of metres apart. At greater depths, these differences become less pronounced. Recharge estimates based on chloride differ markedly from those obtained from tritium. Although the stable isotope values of the underlying saturated zone are similar to moisture in the deeper sections of the unsaturated zone profiles, the markedly lower chloride concentrations point towards preferential or bypass flow as an important mechanism of ground water recharge in the area. This can be regarded as a benchmark site on account of the wealth of unsaturated zone data as well as the detailed and ongoing rainfall record.

1. INTRODUCTION

The aim of this project was to obtain profiles of moisture content, isotopic and chemical indicators of the movement of rain water in the unsaturated zone in appropriate semi-arid environments in southern Africa. The results obtained form part of a world-wide survey of unsaturated zone transport with particular aim of exploiting what may be the last opportunity of applying thermonuclear tritium as a tracer in the unsaturated zone. Since thermonuclear tritium in the southern Hemisphere rain water peaked in 1964, levels have declined to about the expected pre-bomb, or natural, values (IAEA 1992). It is however possible that in thick unconsolidated overburdens thermonuclear tritium might still be found, acting as a marker of water infiltrated during the latter 60's which has not yet completely traversed the unsaturated zone.

During the mid-seventies, the Environmental Isotope Group conducted research on unsaturated zone transport in what is now called Northwest Province of the Republic of South Africa (Verhagen et al. 1979a; 1979b). Sample profiles were obtained in effectively pure sand overburden down to depths of more than 20 metres. Tritium and stable isotope values were measured on the moisture extracted from these samples and conclusions reached on moisture transport.

In the framework of the present project the area was re-visited during late July 1997, and three depth profiles obtained. A further three profiles were obtained in a closely-adjacent location during August 1998. This report describes the sampling procedures and analytical techniques, discusses the results and presents the conclusions drawn from the available information.

2. DESCRIPTION OF STUDY AREA

The area of study (Fig. 1) is typified by flat, featureless terrain with low, semi-fixed dunes, at an altitude of about 1100 m.a.m.s.l. and can be described as semi-arid on the basis of Köppen and Thornthwaite classifications. The sandy surface cover and topography lead to little runoff. Average annual rainfall is 309 mm (6 stations), the average number of rain days per year is 26 and pan evaporation is 2400 mm a^{-1}. The vegetation is typical African bush savannah.

The underlying geology of the area is varied, ranging from the oldest rocks consisting of dolomites, banded ironstones, lavas and tillites, to the lower members of the Karoo sedimentary sequence with intrusives. The hard rocks are covered by the Kalahari deposits, a semi-consolidated sequence which in the study area may reach a thickness of more than 150 m and consists of basal gravels, clays, calcretes and sand. The thickness of the fine, windblown red to white sand cover may exceed 50 m.

3. FIELD WORK

3.1 Drilling programme for 1997

During July 1997, three unsaturated zone profiles were obtained by hand augering in the Hotazel/Black Rock area of South Africa (Fig. 1). The area was chosen in the light of the earlier study (Verhagen et al. 1979a,b) which showed a pure sand cover depth of more than 22m. The profiles sampled in the first year of study reached depths of 18 m, 15 m and 3 m respectively. The first profile (BH 10) was sampled every 1 m; the second (BH 11) every 0.5 m, and the shallow profile (BH 12) was sampled at 0.1 m intervals. For the deeper profiles, 3 kg samples of sand were taken in glass preserve jars and 1 kg parallel samples in tins supplied by the IAEA. The shallow profile samples were taken in tins only.

The augering site was within a few tens of metres of the profile drilled in 1977 on the farm Harefield (Fig. 1). As the area is well-vegetated, the site chosen was in the middle of a grassed clearing about 100 m across between moderately-sized, mainly acacia, trees. Although it was realised that this choice would introduce some bias in terms of vegetal representativeness, the aim was to avoid striking major roots, which previous experience had shown could frustrate hand, and even power, augering. Bh 11 was drilled some 20 m from BH 10. The shallow BH 12 was drilled halfway between them. Fine root material was noticed only down to about 50 cm. The profiles consisted of pure sand, with noticeable changes in colour and texture, somewhat coarser material being encountered at depths greater than 10 m.

The auger used was constructed from thin-walled steel tubing, 10 cm dia, 25 cm long with two inclined cutting blades. The auger stem was made up of 1 m length steel water pipes with threaded ends and standard pipe bushes. This provided a robust, but heavy system. A 4 m tripod with a hook at the top served to stabilise and vertically store the 5-6 m lengths into which the stem was separated during raising and lowering of the auger at greater depths.

A problem encountered was that the auger holes tended to curve away noticeably from the vertical at depths greater than about 10 m. This implied scraping of the auger head along the wall of the hole whilst being lowered and raised. For every augerful sampled, sand was therefore removed off the top and bottom of the contents of the auger, and the centre section transferred directly into the sampling vessel which was immediately closed. The depth of 18m (BH 10) was the maximum attainable with the equipment used, and took about 1.5 days to reach. A second hole (BH 11) was drilled to 15m, reached in about 1 day. BH 12 was drilled to about 3 m, but sampled every 10-15 cm, which took a few hours.

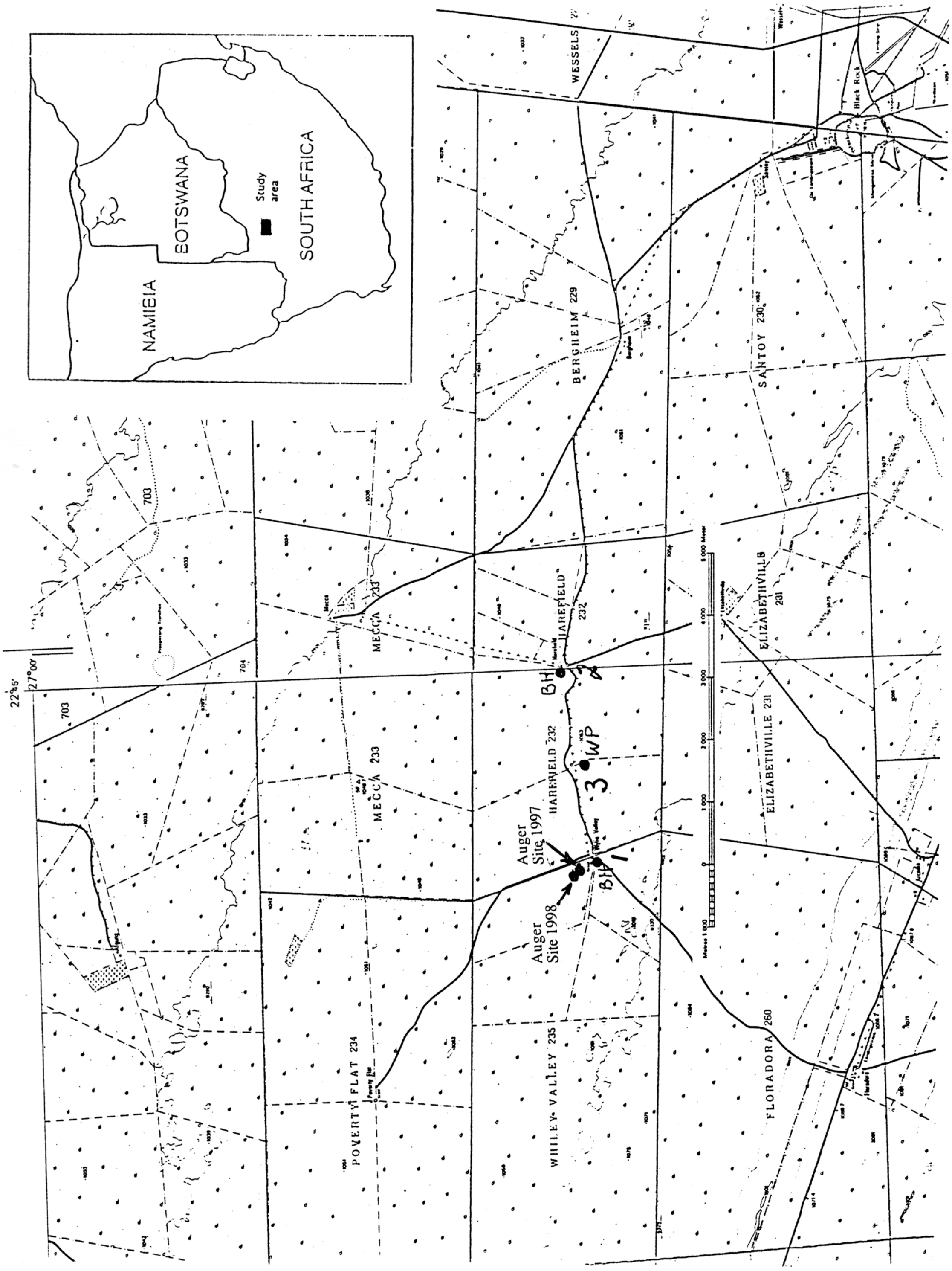

NAMIBIA
BOTSWANA
SOUTH AFRICA
Study area
22°36'
27°00'
703
704
WESSELS
Black Rock
BERGHEIM 229
SANTOY 230
HAREFIELD 232
MECCA 233
ELIZABETHVILLE 231
POVERTY FLAT 234
WHITLEY VALLEY 235
FLORADORA 260
Auger Site 1997
Auger Site 1998
BH 1
BH 2
WP 3

FIGURE 1.

3.2 Drilling programme for 1998

A further three hand auger boreholes were sunk in July 1998 in the same area as, and at a distance of some 70 metres from, the 1997 boreholes, in a different clearing between mainly acacia trees. BH 13 was sunk to 22 m over a period of two days. BH 14 and BH 15 were sunk at a distance of 25 metres to the west and north respectively to a depth of 8 metres. BH 15 struck a major root at a few metres depth. The position was moved about 1 metre and encountered no obstruction.

As with BH 10, 11 and 12 pure sand was encountered in these profiles, which changed in colour and texture with increasing depth. This allowed for assessing the extent of shallower material contaminating the deeper samples visually and removing it before the sample vessels were filled.

Narrower and longer auger heads were tried initially. They were found however to be less effective than the original auger head which was used for the profiles of 1997, and again for sinking BH 13.

Sand samples of 3 kg were taken in glass preserve jars. These were intended principally for tritium analysis. In addition to each of these, four 50 g samples for stable isotope analysis were taken in small glass bottles with double stopper. These were used following the experience gained from the first round of sampling, which showed that stable isotope values started shifting rapidly in tins, and in the larger glass vessels once they had been opened.

4. ANALYTICAL METHODOLOGY

4.1 Moisture contents

About 20g of sand is placed in a petri dish and weighed accurately on a precision balance. It is then placed in a drying oven at about 100°C overnight, allowed to cool and weighed again. The weight difference is taken to be loss of moisture, expressed as a weight percentage w.r.t. the original weight. When water was quantitatively distilled from the larger, 3 kg sand samples, the sample was weighed before and after distillation, as well as the water produced.

4.2 Chloride concentration

About 30 g of moist sand is placed in a small glass bottle, which is weighed accurately and 20 ml of de-ionised water is added. The bottle is tightly stoppered and shaken. It is then left overnight, again shaken, and left to settle. The electrical conductivity of the supernatant is determined with an E.C. meter and the Cl^- concentration is determined with an ion sensitive electrode. The Cl^- value in the soil moisture in both cases is determined by:

$$C_O = \frac{(C - C_i)M_w}{M_s p}$$

where C_O is the value in the soil moisture; C the measured value; C_i the blank value for de-ionised water; M_W the mass of water added; M_S the mass of soil and p the measured weight fraction of water (initial moisture contents).

4.3 Stable isotopes

The analytical procedures for stable isotopes developed during the project are described in some detail as they have some unique features which specifically suit them to unsaturated zone investigations.

4.3.1 *Deuterium*

Deuterium measurements are conducted by using a modification of a method developed by Darling (1989). Ampoules are made from Pyrex glass tubing (Fig. 2) with a constriction. 0.5 g specially prepared and dried Zn metal grains (20-30 mesh) are shaken through the lower constriction. A small plug of glass wool is then inserted and held in position by this constriction. The top of the ampoule is then drawn to a narrow neck, attached to a vacuum line and evacuated whilst heating to some 200$^{\mathrm{o}}$C.

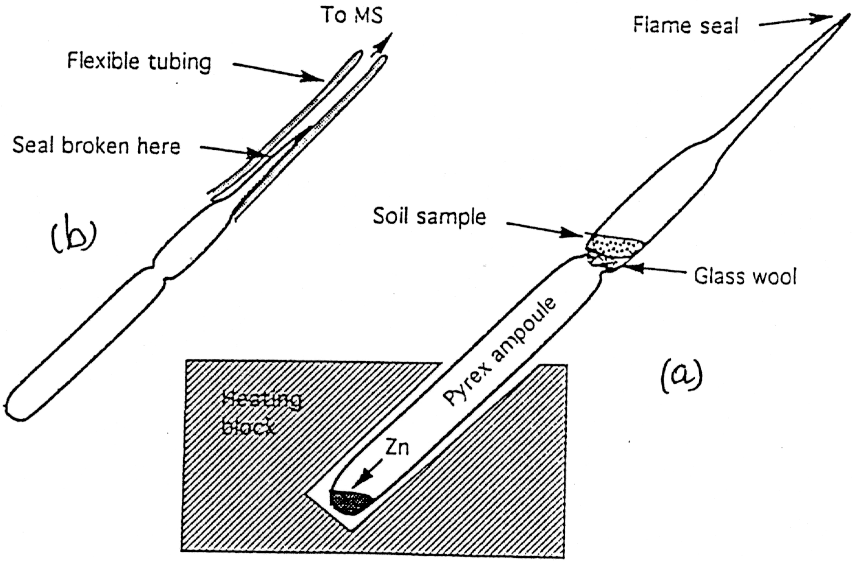


FIGURE 2.

After cooling down, the ampoule is removed from the vacuum line and about 0.5 g of moist sand (depending on the moisture content) shaken rapidly through the neck onto the glass wool. The ampoule is then immediately re-attached to the vacuum line, cooled to -80$^{\mathrm{o}}$C in dry-ice slurry and evacuated. The upper constriction is then flame-sealed. Ten such ampoules can be heated simultaneously at an angle in a heating block at ~ 500$^{\mathrm{o}}$C, with the sand just outside the block (Fig. 2a).

Complete reaction to H_2 is usually achieved within about 30 minutes, and checked by observing the absence of visible moisture condensation after touching the ampoule with a liquid nitrogen-soaked cotton wool plug.

Deuterium is then measured in an isotope VG 602C isotope ratio mass spectrometer. The ampoule is attached to the IRMS inlet with a length of flexible tubing (Fig. 2b). After evacuation, the tip of the ampoule seal is broken by hand through the flexible tube and the hydrogen gas allowed to flow into the IRMS inlet reservoir.

To test the reproducibility of the method, deuterium measurements using the above-mentioned method have been conducted on

1. four aliquots from a moist sand sample and
2. four aliquots of sand, first dried in a drying oven and then moistened with water of known isotopic content.

The results are presented in Table 1.

Table 1. Deuterium test analyses

Sample	δD (‰)	Sample	δD (‰)
Soil Sample 1	-67.8	Wetted Sand 1	-2.2
Soil Sample 2	-66.1	Wetted Sand 2	-2.1
Soil Sample 3	-66.8	Wetted Sand 3	-3.9
Soil Sample 4	-67.3	Wetted Sand 4	-2.4
		Average Water	-2.6

The reproducibility of the δD measurements on the first set of moist samples is very good. The results for the measurements on the second batch of samples again shows good reproducibility as well as acceptable correspondence with the known isotopic value of the water used. The method therefore appears to be quantitative and fractionation corrections therefore need not be applied.

4.3.2 *Oxygen-18*

An approach similar to the direct conversion technique for deuterium was tried in two methods for oxygen-18 determination by equilibrating CO_2 directly with the moist soil/sand.

a) About 1g of sand is placed in a glass ampoule which is attached to a vacuum system via a capillary, pumped and CO_2 admitted. The ampoule is then flame sealed, removed from the vacuum line and left in a horizontal position to equilibrate. The CO_2 is transferred to the mass spectrometer inlet as described for deuterium measurements (above). It was found that oxygen isotope equilibration between the sand moisture and CO_2 proceeded rapidly, and was complete within a few hours. Reproducibility for duplicate samples was as good as for standard water equilibration.

b) The second method uses the water equilibration line for oxygen-18 determination. The advantage is that 17 aliquots can be handled simultaneously. Sand samples are weighed into individual bottles which are attached to the line. The bottles are evacuated through individual capillaries and CO_2 admitted. The bottles are left stationary, as the sand would not move under the shaking motion. It was found initially that equilibration proceeded only partially, the CO_2 not reaching the expected isotopic composition even after 24 hours. It was concluded that only the moisture in the uppermost layers of the sand sample was brought into mixing contact with the free CO_2 overlying the sand. The procedure was then changed by bringing the bottles into a near-horizontal position and tapping them gently, in order for the sand to spread out and develop cracks in its bulk. It was found that under these (again stationary) circumstances, equilibration was complete in about 4 hours (Fig. 3). As with the first method, good reproducibility could be obtained in duplicate samples.

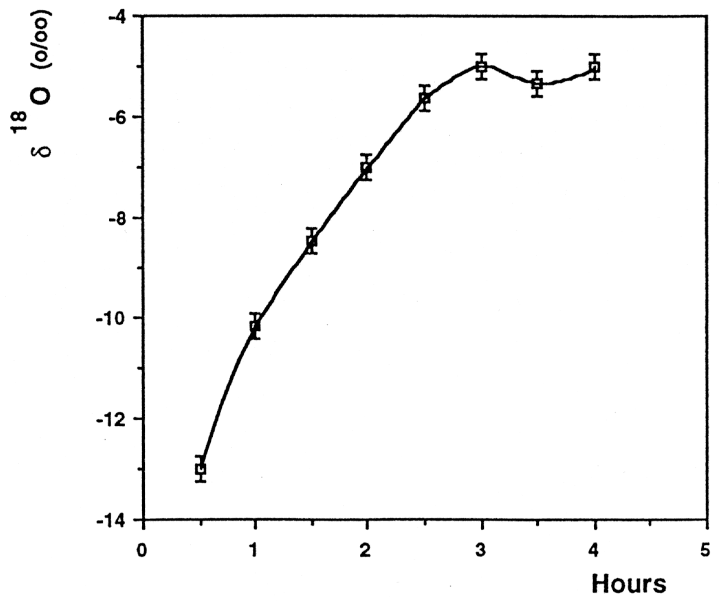


FIGURE 3.

As the moisture content of some of the augered sand samples was rather low (<2 wt.%), an amount correction may have to be applied to the measured $\delta^{18}O$ values. This correction (IAEA 1981) is given by:

$$\delta_G^0 = (1 + \alpha \frac{n}{N})\delta_G - \alpha \frac{n}{N} \delta_G^i$$

where n and N are the gram-atoms of oxygen in the sample and CO_2 respectively; α is the fractionation factor; δ_G is the value for CO_2 after equilibration, δ_G^0 the value for an infinite amount of water (n/N = 0); δ_G^i is the initial value of CO_2.

A test with standard water samples was run on the method, using the same gas both as the reference and for equilibration. An amount of sand typical for the study area was thoroughly dried and 20 g aliquots loaded into equilibrator bottles. Water standards were pipetted into the individual bottles to produce a 2% by weight moisture contents, the bottles were stoppered and shaken to homogenise the moisture. Duplicate bottles of each: SLAP, VSMOW, GISP and eight of a lab standard were then attached to the equilibration line and handled in the standard fashion for oxygen-18 analysis. The results are shown in Table 2.

The duplicate values of $\delta^{18}O$ for the standards and the multiple values for the lab standard show very good reproducibility (21.50 ± 0.13 ‰). The span between SMOW and SLAP is considerably lower than the theoretical value. In spite of this, the span corrected value for GISP is δ_{SMOW} = -24.86 ‰ and for the lab standard the accepted value of -0.58 ‰ is obtained.

The corrections which would have to be applied to the results in terms of the moisture content of the sand needed to be assessed. Typical sand from the project area was thoroughly dried, moistened with a laboratory water standard to water contents ranging from 2% to 10%, and subjected to typical equilibration with CO_2. The resulting $\delta^{18}O$ values are shown in Fig. 4. Interestingly, the results follow an exponential dependence on moisture contents, which allows the results to be corrected using the best-fit exponential expression.

Table 2. Results of water standards

Laboratory Standard	$\delta^{18}O$ (‰)
SMOW (a)	+21.89
SMOW (b)	+22.08
SLAP (a)	-24.32
SLAP (b)	-24.14
GISP (a)	+1.24
GISP (b)	+1.33
TAP Std (a)	+21.42
TAP Std (b)	+21.60
TAP Std (c)	+21.28
TAP Std (d)	+21.37
TAP Std (e)	+21.54
TAP Std (f)	+21.61
TAP Std (g)	+21.68
TAP Std (h)	+21.52

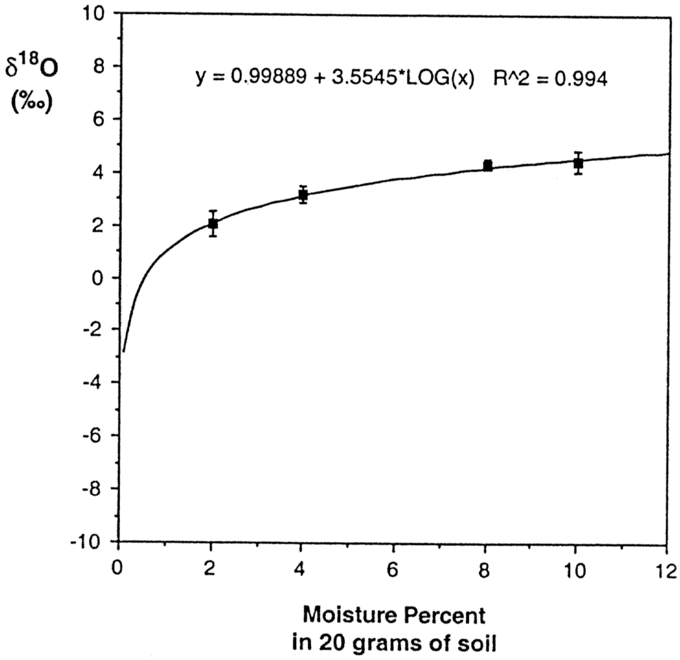


FIGURE 4.

4.3.3. *Tritium*

The entire contents of a 3 kg jar is weighed and then emptied into a metal vessel. The lid of the vessel has a vacuum tight seal and a conical joint on which is mounted a Liebig condenser with a 1 litre collection flask and a capillary connection to a vacuum pump. The metal vessel is first evacuated through the capillary (to limit the loss of water vapour) and then heated to about 100°C. The distillation proceeds until the sand is dry. Both the sand and the collected water are weighed. Typical moisture recovery is around 95%. The resulting fractionation is too small significantly to influence the tritium values.

Aliquots of 110 ml of water are made up, either from a single soil sample if it yielded enough water, or by adding some water from the previous, or following, sample. Sodium peroxide is added to the water to make a 2% NaOH solution and batches of samples are electrolysed to a final volume of 15 ml. The resulting enrichment in tritium is about 6x. A zero tritium blank sample and a tritium spike is run with each batch. The enriched samples are then vacuum distilled. A 10 ml sample is introduced into a standard counting vial, Ultima Gold scintillator is added, shaken and counted in a Packard 2770 TR/SL low-level liquid scintillation counter.

5. RAINFALL DATA

The owner of the farm Harefield had kept meticulous rainfall records since 1966 which are shown in Table 3 and Fig. 5. A few salient features are noted:

1. The rainfall is strongly seasonal. The wettest months are November - March. During the winter months May - August, rainfall is rare.
2. The rainfall for individual months is highly variable from year to year.
3. There is the suggestion of a cycle in annual totals of the order of 11 years (cf. long-term mean of 337 mm a^{-1}).
4. Unusually late rains fell shortly before the profiles were taken in July 1997.

6. THE SATURATED ZONE

The three boreholes sampled were all drilled into the basal gravels of the Kalahari sequence. In 1977 the rest levels in the area lay in the range of 70-80m (Verhagen et. al 1979(b)). Isotope and other observations on pumped water from the three boreholes are given in Table 4.

In all cases the radiocarbon values are rather low, the result for the Harefield pumped borehole suggesting that confined water is being extracted. If the deep aquifer is represented by the value of the pumped borehole on Harefield, then the Wylie Valley borehole can be interpreted as pumping a mixture of the old, confined and more recent ground water, overlying the clay. The Harefield wind pump (KSP 3) at 48 pMC produces much more recent water, with significantly more positive stable isotope values.

The model which emerges from these observations is the following. When infiltrating rain water reaches the saturated zone, it recharges the upper aquifer. The lower, below the aquitard/aquiclude, is said to be sub-artesian. The deeper aquifer will therefore react only very slowly, if at all, to such recharge events. Evapotranspirative losses will be more pronounced from the shallow, phreatic aquifer, which therefore becomes ephemeral. Following the high rainfall period 1973-75 (Fig. 5), there is a suggestion of significant rest level rises in the area. Based on the unsaturated zone profiles obtained in 1977, an infiltration rate of the order of 15% of mean annual rainfall was derived for the high rainfall period. Although the radiocarbon values are low, suggesting MRT values for the ground water in the range of 3000 years and greater, these should be interpreted in terms of the mixture of ground water likely to be produced by the deep boreholes

Table 3. Rainfall Data for Harefield Farm

	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81
	65/66	66/67	67/68	68/69	69/70	70/71	71/72	72/73	73/74	74/75	75/76	76/77	77/78	78/79	79/80	80/81
Sep	0	0	0	0	0	0	0	0	0	8	3	9	40	15	12	16
Oct	0	7	0	30	13	0	24	0	41	10	0	23	23	6	58	0
Nov	17	0	2	0	9	30	5	25	50	28	42	3	39	2	7	81
Dec	3	25	7	36	19	16	67	0	106	18	211	7	76	23	36	18
Jan	47	81	38	18	16	29	127	5	191	85	218	104	38	47	18	34
Feb	46	93	0	66	20	102	12	106	121	19	55	51	80	171	74	103
Mar	8	25	43	6	0	56	114	85	251	54	156	280	77	11	52	39
Apr	11	42	40	76	31	11	80	68	31	43	68	39	19	22	17	0
May	0	49	68	17	19	46	0	0	16	7	13	0	0	0	0	0
Jun	11	0	13	0	9	0	0	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	8	0	0	0	0	31	0	0	0	0	12	50
	143	322	211	249	144	290	429	289	807	303	766	516	392	297	286	341
	337	337	337	337	337	337	337	337	337	337	337	337	337	337	337	337

	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	
	81/82	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90	90/91	91/92	92/93	93/94	94/95	95/96	96/97	Average
Sep	0	0	3	0	13	41	36	15	0	0	0	0	0	0	0	4	#DIV/0!
Oct	31	77	6	18	10	0	5	11	0	0	12	8	88	2	14	0	#DIV/0!
Nov	108	37	75	23	7	32	33	37	22	0	8	25	22	0	26	74	74
Dec	92	17	73	9	83	33	37	118	25	50	28	17	12	15	74	75	#DIV/0!
Jan	0	40	17	41	9	55	21	169	48	128	0	16	29	34	49	109	6
Feb	70	0	0	59	47	212	206	59	54	81	16	115	40	0	71	33	15
Mar	17	29	94	23	17	62	49	17	28	169	44	23	56	84	0		21
Apr	33	31	13	9	14	60	77	112	73	0	11	0	0	0	13	40	42
May	0	12	22	0	8	0	7	30	0	0	0	0	0	26	6	37	69
Jun	0	7	0	0	7	0	0	0	0	43	0	0	0	0			70
Jul	17	0	0	0	0	0	0	0	0	0	0	0	0	0			79
Aug	0	0	0	0	0	0	0	0	0	0	0	0	0	0			37
	368	250	303	182	215	495	471	568	250	471	119	204	247	161	253	372	#DIV/0!
	337	337	337	337	337	337	337	337	337	337	337	337	337	337	337	337	337

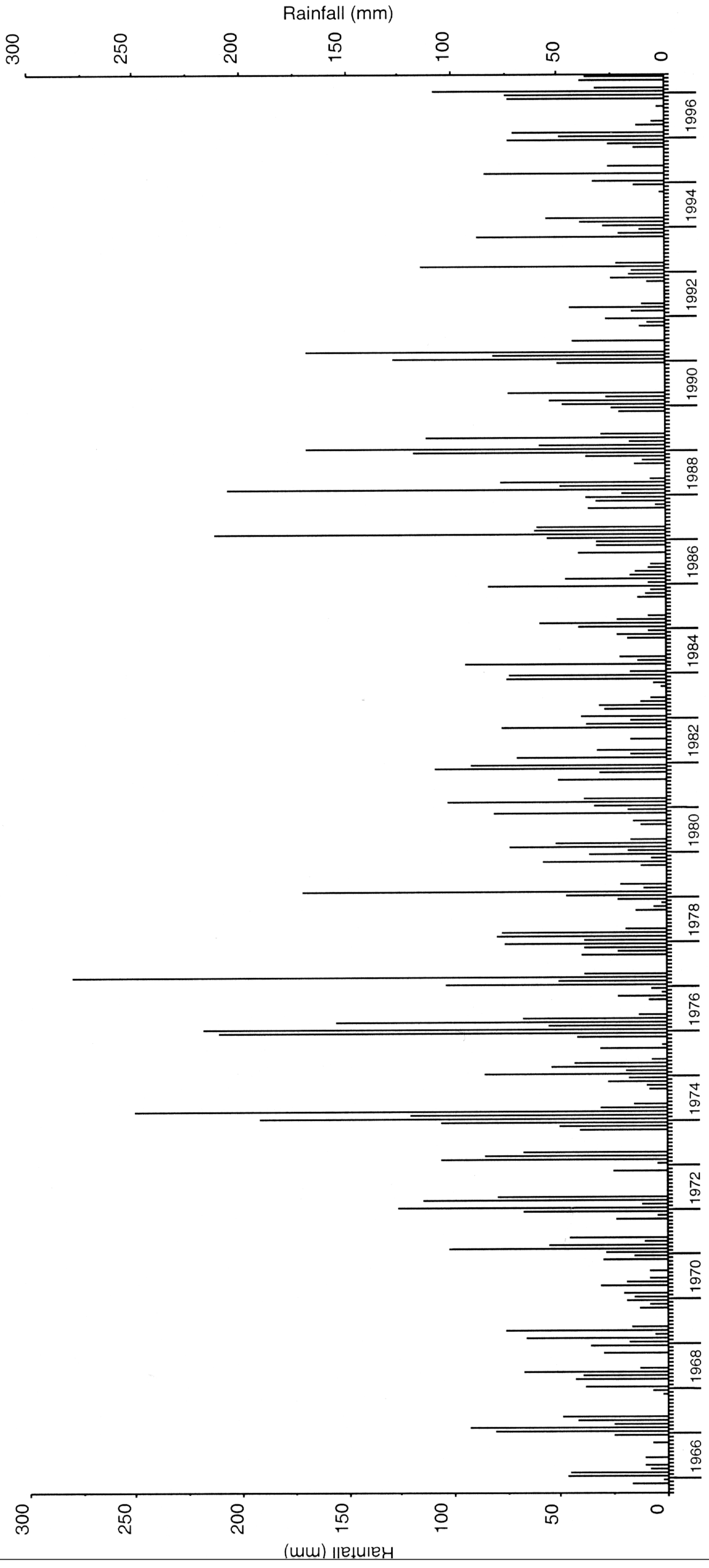

Rainfall (mm)
300
250
200
150
100
50
0
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
Rainfall (mm)
300
250
200
150
100
50
0

FIGURE 5.

Table 4. Borehole Data

Sample	Radiocarbon (pMC)	$\delta^{18}O$ (‰)	δD (‰)	[Cl] (mg/l)	E.C. (μS/cm)
KSP 1	33.6±1.6	-5.97	-41.5	34	300
KSP 2	9.2±1.4	-5.88	-39.6	90	670
KSP 3	48.2±1.7	-5.22	-35.7	88	660
Wylie V WP 1977	36.8	-5.80	-38.0		300

7. DATA FROM THE PROFILES

The results of the measurements on sand samples from the different auger boreholes taken during 1997 and 1998 are shown in Tables 5 to 10 and in Figs. 6 to 11.

These results are discussed in terms of each of the two sampling periods.

7.1 The 1997 Profiles: BH 10; BH 11; BH 12

7.1.1 *Moisture*

The moisture content of all three profiles shows a high near the surface. This suggests the influence of the relatively good 1996/97 (and possibly 1995/96) rainy seasons and the above-average late-season rain which had fallen in the area (see Table 3 and Fig. 5). The high is then followed in all three cases by a minimum around 1 metre; a maximum around three metres and then a gradual increase for Bh 10 and Bh 11 to a value of some 2.3 % near the bottom.

7.1.2 *Oxygen-18*

The inflection in $\delta^{18}O$ at the very top of the profile, typical of the evaporation front (Allison et al 1994; Barnes and Allison 1988), is not observed, even with the finer depth resolution in BH 12. The first ~ 0.10 metres of the sand column was effectively dry. There is a general decline in $\delta^{18}O$ values, the shapes of the observed curves placing them in the category of profiles characteristic of low recharge (Allison et al. 1994).

In BH 12 the top-most $\delta^{18}O$ value shows extreme enrichment which suggests that the upward trend in the $\delta^{18}O$ profiles for the other auger holes may continue to the surface. A strong transient drying condition following the rains which fell shortly before might have been recorded in this sampling episode. It might be speculated whether an inflection might have been recorded in the $\delta^{18}O$ profile for BH 12 had it been sampled at even smaller intervals. The rest of the profile gives values considerably more positive than for corresponding depths in the other two. It is as yet unclear whether this difference is an artifice of the measurements.

7.1.3 *Electrical conductivity and chloride concentration.*

The profiles of EC and Cl^- concentrations for BH 10 show strong similarities. This suggests that chloride makes up an important component of the overall mineralisation of the soil moisture. For the first 10 metres or so these parameters increase with increasing moisture content. It appears that near-surface mineralisation, increased by evaporation, is being washed down by successive infiltration events. The broad minimum between -11 m and -16 m coincides with a

Table 5. Borehole 10

Lab No.	Depth (m)	$\delta^{18}O$ (‰)	Tritium (TU)	Moisture %	Chloride (ppm)	E.C. (μmhos)
KSP 4	0.3	+1.85	11.2±0.6	1.84	1316	2718
KSP 5	1.0	-1.90		1.08	630	1940
KSP 6	2.0	-2.97		1.92	337	1039
KSP 7	3.0	-2.82	7.2±0.5	1.85	964	3515
KSP 8	4.0	-3.86		1.57	746	1909
KSP 9	5.0	-5.59		1.55	355	812
KSP 10	6.0	-5.37	6.6±0.5	1.71	373	1168
KSP 11	7.0	-4.78		2.10	463	1380
KSP 12	8.0	-5.13		1.87	210	728
KSP 13	9.0	-6.55	7.3±0.5	2.35	286	959
KSP 14	10.0	-5.93		2.28	391	1537
KSP 15	11.0	-6.71		2.17	189	1013
KSP 16	12.0	-6.53	6.9±0.5	2.16	195	1293
KSP 17	13.0	-6.93		1.89	219	1191
KSP 18	14.0	-7.48	7.6±0.5	1.97	185	1457
KSP 19	15.0	-7.49		2.21	205	1403
KSP 20	16.0	-7.23	13.5±0.8	2.02	229	1484
KSP 21	17.0	-7.29		2.18	588	1837
KSP 22	18.0	-6.50	8.1±0.6	2.33	525	2465

Table 6. Borehole 11

Lab No.	Depth (m)	$\delta^{18}O$ (‰)	Moisture %	Chloride (ppm)	E.C. (μmhos)
KSP 23	0.5	+0.09	3.11	152	270
KSP 24	1.0	-2.56	1.57	306	510
KSP 53	1.2	-1.34	1.64	265	468
KSP 25	1.6	-2.72	1.45	367	483
KSP 26	2.0	-1.98	1.56	234	481
KSP 27	2.4	-1.76	1.96	259	509
KSP 28	2.8	-2.10	2.24	178	335
KSP 54	3.0	-1.91	2.28	350	438
KSP 29	3.5	-2.89	2.34	206	320
KSP 30	4.0	-2.91	2.04	199	425
KSP 31	4.5	-3.52	2.14	257	552
KSP 32	5.0	-5.00	1.54	401	812
KSP 33	5.5	-4.79	1.69	830	1365
KSP 34	6.0	-4.83	1.70	268	708
KSP 35	6.5	-4.65	1.61	206	497
KSP 36	7.0	-4.74	1.67	255	660
KSP 37	7.5	-5.27	1.80	362	974
KSP 38	8.0	-5.77	2.05	289	978
KSP 39	8.5	-5.57	2.14	655	1770
KSP 40	9.0	-6.70	2.14	430	623
KSP 41	9.5	-5.35	2.21	171	544
KSP 42	10.0	-5.36	1.95	258	700
KSP 43	10.5	-5.68	1.87	394	1739
KSP 44	11.0	-6.34	2.28	221	745
KSP 45	11.5	-6.90	2.14	243	983
KSP 46	12.1	-6.38	2.18	288	893
KSP 47	12.6	-6.63	2.11	275	1406
KSP 48	13.1	-5.56	2.14	242	1356
KSP 49	13.6	-6.40	2.05	286	1446
KSP 50	14.1	-6.91	2.19	279	1200
KSP 51	14.6	-6.65	2.13	238	1249
KSP 52	15.0	-6.69	2.35	66	1468

Table 7. Borehole 12

Lab No.	Depth (m)	$\delta^{18}O$ (‰)	Moisture %
KSP 55	0.10	+8.82	2.98
KSP 56	0.25	+3.57	2.56
KSP 57	0.35	+2.44	2.79
KSP 58	0.45	+1.56	2.91
KSP 59	0.55	+2.24	1.48
KSP 60	0.60	+1.42	1.96
KSP 61	0.75	+2.75	1.00
KSP 62	0.85	+1.39	1.00
KSP 63	1.00	+1.21	1.08
KSP 64	1.10	+1.71	1.09
KSP 65	1.25	-1.56	1.17
KSP 66	1.35	-1.98	1.26
KSP 67	1.45	+0.75	1.30
KSP 68	1.55	-0.14	1.22
KSP 69	1.70	-0.13	1.33
KSP 70	1.80	-1.01	1.40
KSP 71	1.95	-1.11	1.58
KSP 72	2.05	-0.05	1.69
KSP 73	2.15	+0.54	1.65
KSP 74	2.30	-0.47	1.64
KSP 75	2.40	+0.83	1.65
KSP 76	2.55	-0.34	2.01
KSP 77	2.65	+0.68	2.22
KSP 78	2.80	-0.38	2.27

Table 8. Borehole 13

Lab No.	Depth (m)	$\delta^{18}O$ (‰)	δD (‰)	Deuterium Excess	Tritium (T.U.)	Moisture %	Chloride (ppm)	E.C. (μmhos)
KSP 79	0.5	-2.02	-16.5	-0.34		1.09	334	1614
KSP 80	1.0	-2.25			6.1±0.7	1.09	239	1615
KSP 81	1.5	-1.86	-24.8	-9.92		1.71	79	965
KSP 82	2.0	-0.87				1.71	118	755
KSP 83	2.5	-2.04	-36	-19.68		0.97	411	2349
KSP 84	3.0	-0.38			3.5±0.6	0.97	317	1471
KSP 85	3.5	-1.28	-18.2	-7.96		1.67	222	1051
KSP 86	4.0	-2.11				1.67	142	705
KSP 87	4.5	-2.3	-13.5	4.9		1.78	101	571
KSP 88	5.0	-2.51			3.2±0.6	1.78	133	694
KSP 89	5.5	-2.2	-20.5	-2.9		1.92	193	1077
KSP 90	6.0	-3.02				1.92	131	669
KSP 91	6.5	-3.68	-31.5	-2.06	5.7±0.7	2.05	132	538
KSP 92	7.0	-4.91				2.05	48	361
KSP 93	7.5	-4.74	-28	9.92	6.0±0.7	2.06	96	812
KSP 94	8.0	-4.61				2.06	176	763
KSP 95	8.5	-4.86	-33.4	5.48	3.3±0.6	2.33	116	508
KSP 96	9.0	-4.71				2.33	82	339
KSP 97	9.5	-4.98	-37.8	2.04	4.7±0.7	2.41	84	546
KSP 98	10.0	-5.12				2.41	78	685
KSP 99	10.5	-5.04	-39.7	0.62		2.25	84	741
KSP 100	11.0	-4.78				2.25	80	546
KSP 101	11.5	-4.86	-37.4	1.48	5.9±0.7	2.36	121	1053
KSP 102	12.0	-4.6				2.36	60	596
KSP 103	12.5	-4.66	-32.4	4.88	5.4±0.7	2.33	146	1382
KSP 104	13.0	-4.37				2.33	163	1242
KSP 105	13.5	-5.03	-30.8	9.44	6.5±0.7	2.40	166	1290
KSP 106	14.0	-5.84				2.40	146	1255
KSP 107	14.5	-5.56	-36.6	7.88	4.4±0.6	2.14	167	1502
KSP 108	15.0	-5.73				2.14	214	2373
KSP 109	15.5	-5.6	-37.9	6.9		2.56	130	1877
KSP 110	16.0	-5.39				2.56	110	1002
KSP 111	16.5	-5.73	-35.2	10.64	4.3±0.6	2.39	176	2116
KSP 112	17.0	-5.46				2.39	164	2635
KSP 113	17.5	-5.09	-31.8	8.92	4.3±0.6	2.62	153	1979
KSP 114	18.0	-3.66				2.62	129	1932
KSP 115	18.5	-4.72	-27.2	10.56		2.51	120	1309
KSP 116	19.0	-4.7				2.51	162	1783
KSP 117	19.5	-3.64	-25.9	3.22	5.5±0.7	2.49	135	1754
KSP 118	20.0	-3.12				2.49	151	1938
KSP 119	20.5	-1.96	-25.4	-9.72		3.00	115	1672
KSP 120	21.0	-2.32				3.00	146	1551
KSP 121	21.5	-2.86	-25.7	-2.82	5.2±0.7	2.93	132	1452
KSP 122	22.0	-2.85				2.93	127	1463

Table 9. Borehole 14

Lab No.	Depth (m)	$\delta^{18}O$ (‰)	Moisture %	Chloride (ppm)	E.C. (μmhos)
KSP 139	0.5	-1.86	0.66	629	2851
KSP 140	1.0	-3.09	1.36	170	457
KSP 141	1.5	-1.19	2.10	177	565
KSP 142	2.0	-1.02	1.51	167	405
KSP 143	2.5	-1.15	1.30	208	480
KSP 144	3.0	-0.27	1.51	196	447
KSP 145	3.5	-1.52	1.10	281	808
KSP 146	4.0	-1.89	1.44	221	440
KSP 147	4.5	-1.81	1.68	219	536
KSP 148	5.0	-2.18	1.35	303	1347
KSP 149	5.5	-2.34	1.03	440	2098
KSP 150	6.0	-2.69	1.63	231	509
KSP 151	6.5	-2.58	1.74	218	870
KSP 152	7.0	-3.17	1.26	228	564
KSP 153	7.5	-3.87	2.15	161	719
KSP 154	8.0	-3.09	1.92	214	891

Table 10. Borehole 15

Lab No.	Depth (m)	$\delta^{18}O$ (‰)	Moisture %	Chloride (ppm)	E.C. (μmhos)
KSP 123	0.5	-1.8	1.04	128	496
KSP 124	1.0	-2.24	0.97	167	504
KSP 125	1.5	-1.84	0.94	200	1043
KSP 126	2.0	-0.62	1.28	157	764
KSP 127	2.5	-1.44	1.08	182	812
KSP 128	3.0	-0.99	0.77	262	1234
KSP 129	3.5	-1.72	1.06	223	773
KSP 130	4.0	-2.22	1.41	174	973
KSP 131	4.5	-1.74	1.75	261	1107
KSP 132	5.0	-2.27	1.16	413	1885
KSP 133	5.5	-4.02	1.30	257	1368
KSP 134	6.0	-3.51	1.62	215	969
KSP 135	6.5	-4.73	1.64	389	1564
KSP 136	7.0	-4.9	1.67	184	708
KSP 137	7.5	-6.07	1.65	191	969
KSP 138	8.0	-5.98	1.99	176	491

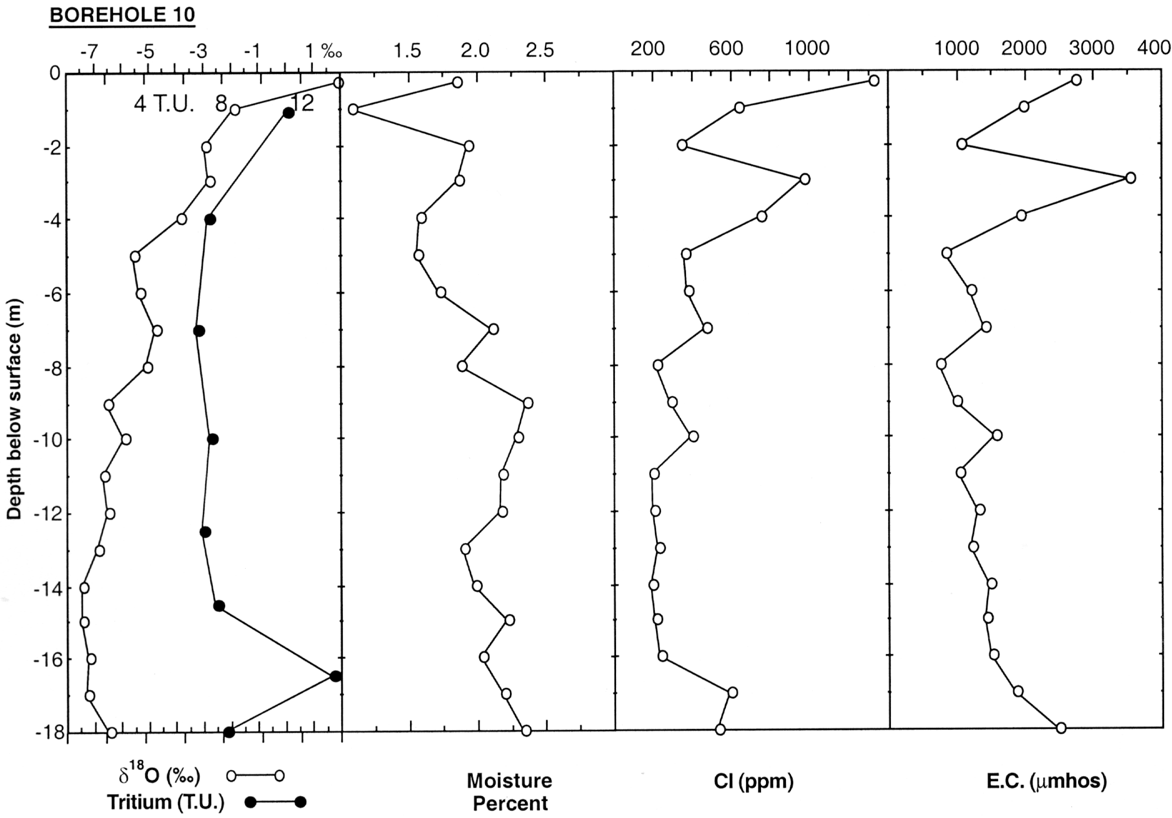


FIGURE 6.

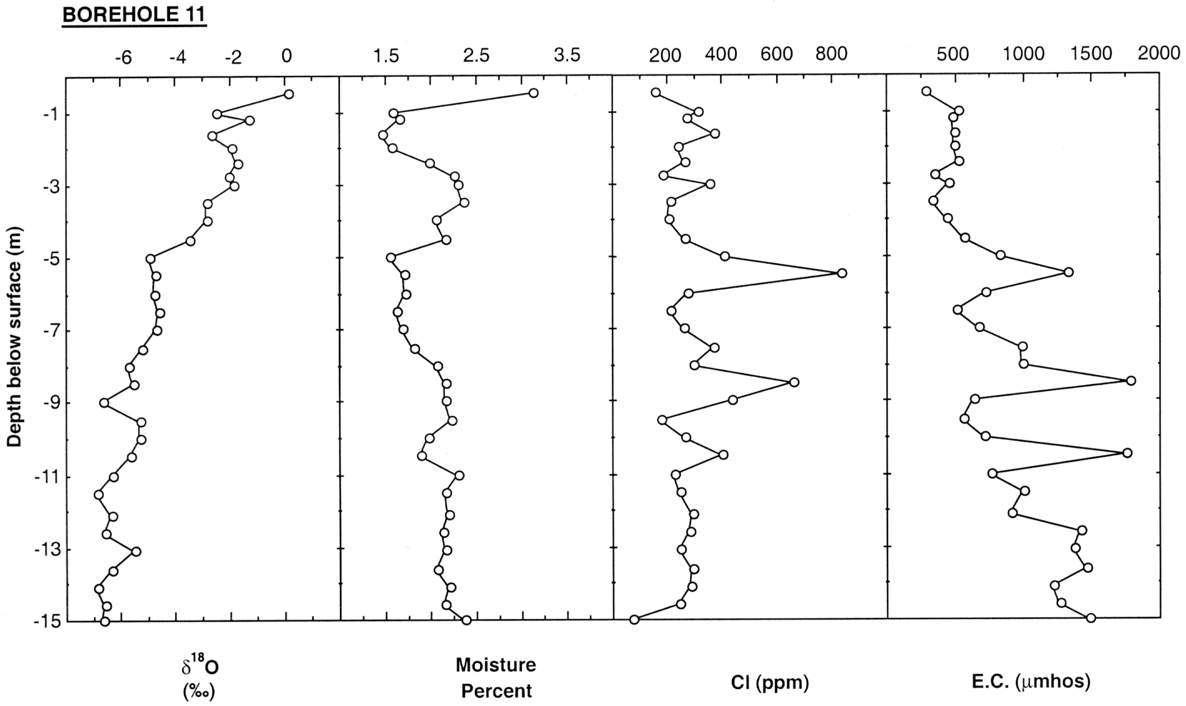


FIGURE 7.

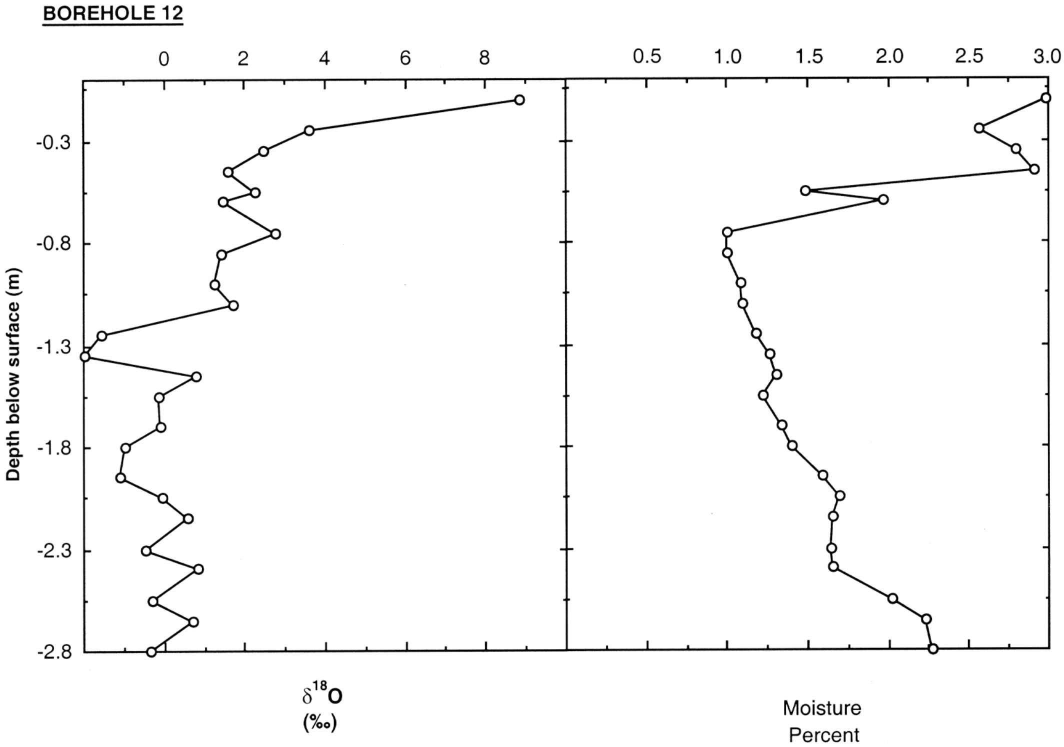


FIGURE 8

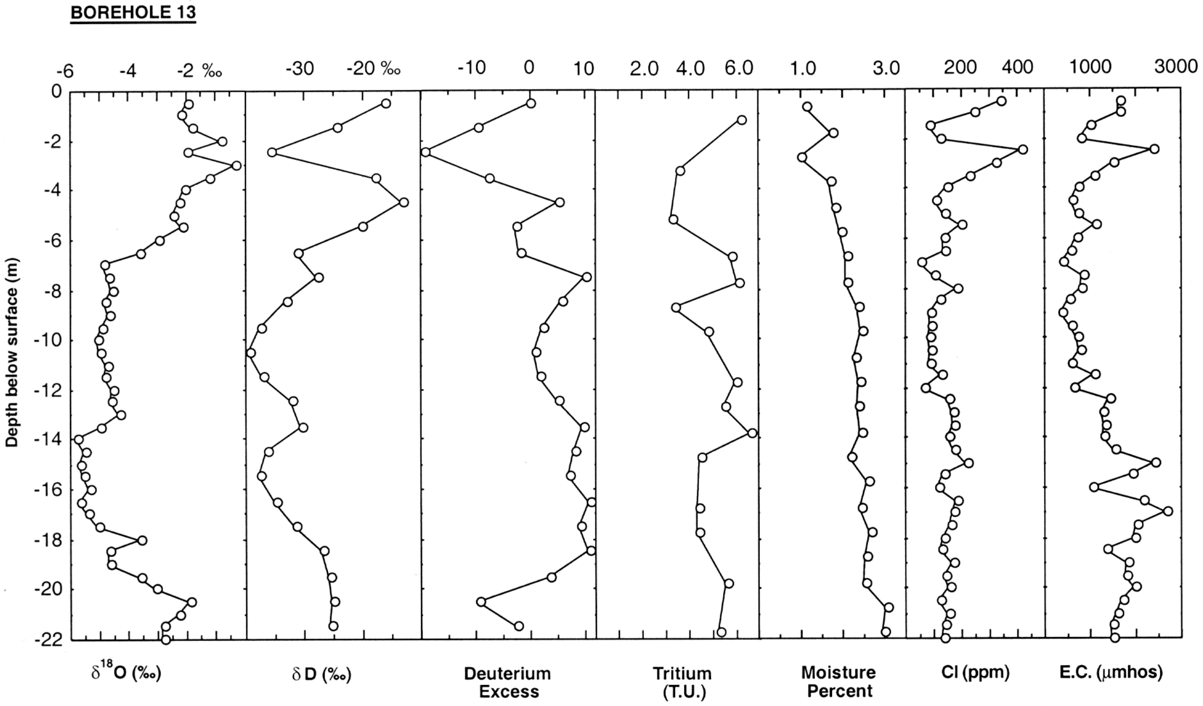


FIGURE 9.

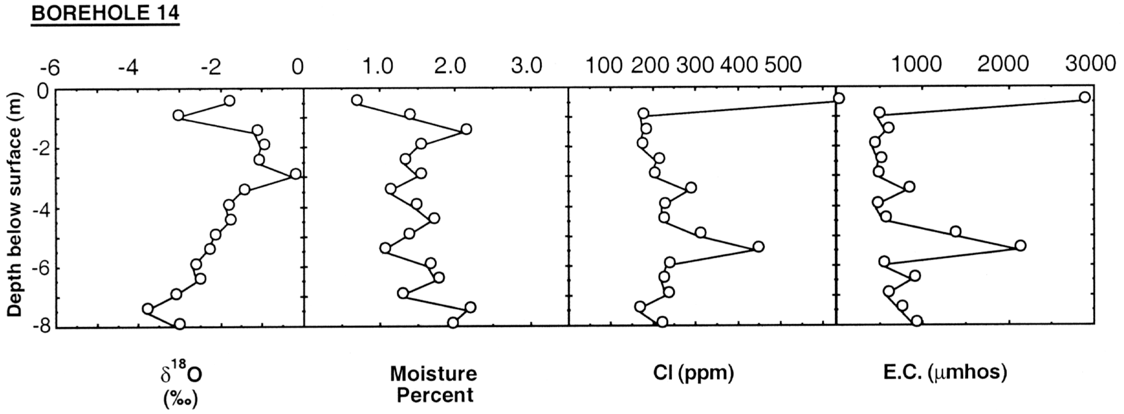


FIGURE 10

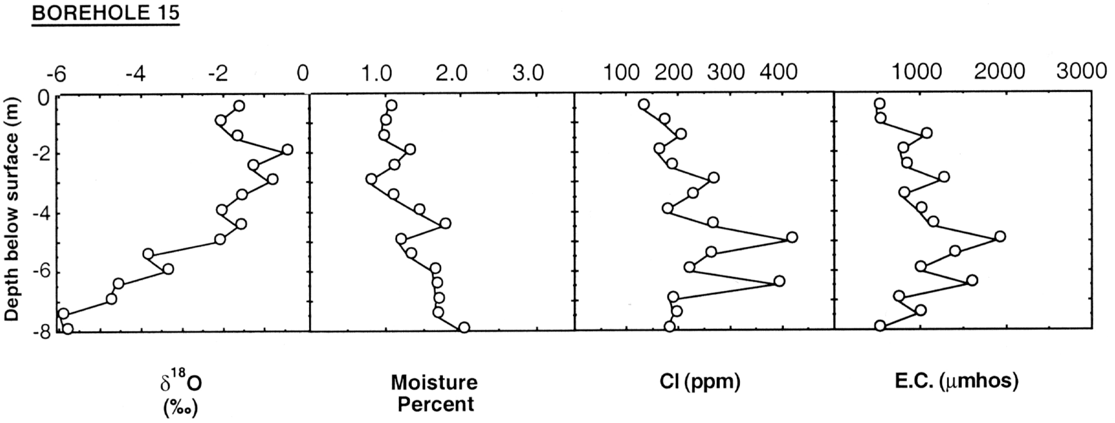


FIGURE 11

minimum in the $\delta^{18}O$ profile. All three parameters show a further rise near the bottom, which may represent the trailing edge of a displacement front. At this depth too, there is an erratic, but general increase in moisture content.

The relative shapes of the EC and Cl^- curves for BH 10 show EC/[Cl^-] ratios ranging from about 3 to about 7. This is reversed near the surface, where the ratio drops to about 0.4, the EC probably representing almost pure chloride. Elsewhere, there is a substantial concentration of other ions, probably mainly HCO_3, which become quite dominant in the -11m to -16m zone, where the ratio rises to 7. This might identify the zone as being associated with a significant recharge period, on account of the increase in biogenic soil CO_2.

The profiles of EC and Cl^- values for BH 11 differ in many ways from those of BH 10. The lower values near the top of the profile seem to reflect the relatively higher moisture contents there. In contrast to BH 10, Cl^- tends to be more prominent with an isolated peak at about -6.5 m. The tendency for the other ions, probably mainly HCO_3, to dominate, seen deeper in BH 10, is also evident here, at roughly the same values. Overall, there is much less correlation between EC and Cl^- values, and moisture and $\delta^{18}O$ profiles than seen in BH 10.

It is remarkable that the behaviour of these parameters can differ so greatly between profiles which are separated laterally by a distance roughly equalling their depths.

7.1.4 *Tritium*

In the 1997 sample set, tritium was measured only in 1998 and then only for BH 10. The results are presented in Table 5 and displayed in Fig. 6. Values higher than expected for average present-day rainfall are observed all the way down the profile. At 0 - 2 m and 16 - 17 m somewhat higher values are observed. These are not interpreted readily. Expected rainfall tritium values for 1997 in the area should lie around 5 TU. However, tritium values up to 15 TU were measured in rainfall samples taken at Johannesburg during the exceptional 1995/96 rainy season which produced monsoon-type conditions from southwards-moving tropical air masses.

When samples for tritium analysis were distilled during 1998, they included a zero sample which was made up by moistening a 3 kg thoroughly dried sand sample to 2% by weight with water at 0 TU. The water was retrieved by distillation and electrolysed as for the auger samples. The enrichment-corrected result of 0.0±0.3 TU suggests that there is minimal tritium contamination during the entire laboratory sample handling procedure.

7.2 1998 Profiles: BH 13; BH 14; BH 15

7.2.1. *Moisture contents.*

Moisture was quantitatively distilled from the 3 kg samples for tritium analysis for BH 13. The moisture content was determined by weighing the entire sample before and after distillation. In the case of BH 14 and 15, sand aliquots were removed from the 3 kg samples and weighed before and after drying in the oven. The results are shown in Figs. 9, 10 and 11.

Compared with the 1997 profiles, the BH 13,14,15 showed much lower moisture content just below surface. This is ascribed to the absence of any rainfall for several weeks prior to sampling. As in the earlier profiles, the uppermost 8 metres or so show considerable variations with depth as well as differences in depth dependence over relatively small lateral distances. As in the 1997 results, the profiles become smoother at greater depths. The moisture profiles of the deeper boreholes BH 10, 11, 13 are compared in Fig. 12 and are quite similar, steadily increasing with depth in all three.

As yet, the controls on these moisture variations are not clear. A possible control could be found in the grain size distribution, as was observed in the profiles obtained in the earlier study of 1977.

7.2.2 *Electrical conductivity and chloride concentrations*

To depths of some 8 m the EC and Cl^- profiles for the deep boreholes BH 10 and BH 13 profiles are quite similar. As was observed for BH 10, the EC for the upper part of the BH 13 profile is dominated by Cl^-. Between 8 and 22 m, Cl^- values increase slightly from about 100 ppm to 150 ppm, whilst EC values increase from about 600 µS to well over 2000 µS. The ratio EC/[Cl^-] ranges from 5 - 7 near the top of the profile, increasing to 10 - 15 near the bottom. This suggests the presence of at least one other ion, which, in the case of BH 10, was speculated to be HCO_3. This relative increase in HCO_3, and lower values of Cl^-, both suggest higher recharge rates with concomitant increase in vegetal activity and release of biogenic CO_2.

7.2.3. *Oxygen-18*

Whereas the $\delta^{18}O$ profiles of BH 10,11,12 exhibited a sharp drop from positive values over the first metre or so from surface, no such drop is seen in the profiles for BH 13,14,15. The latter, taken shortly after late-season rain, show an increase in values down to some 4 m, and then

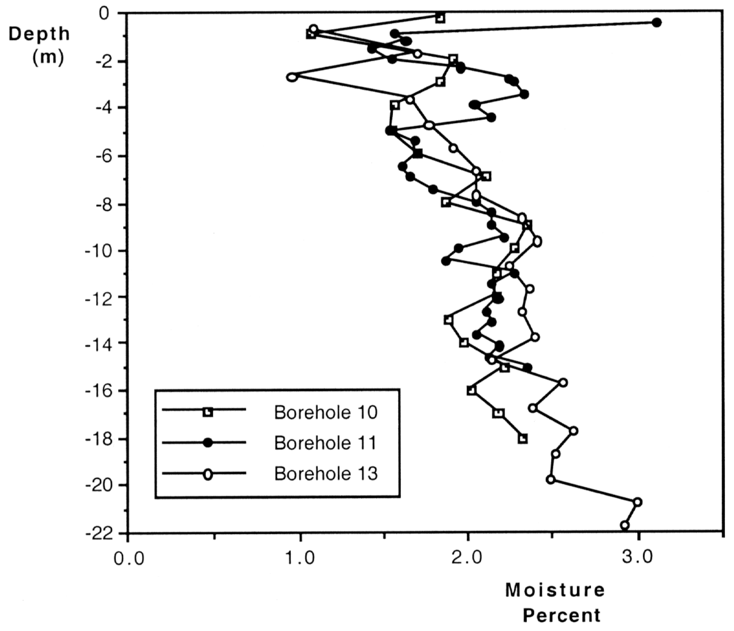


FIGURE 12

a decline to about 8 m. From there, BH 13 shows fairly constant values with a further minimum at 14 - 17 m. Then follows a marked increase down to 22 m. A minimum at about 14 m is also suggested in the $\delta^{18}O$ profiles of BH 10,11, but at values more negative than for BH 13.

All the $\delta^{18}O$ profiles analysed to date are plotted in Fig. 13 for comparison. Although there are considerable differences in the individual profiles, some general trends are observed:

i. Only the 1997 profiles rise to values of 0 ‰ and more positive.
ii. Around 2 m, all profiles lie in the range 0 ‰ to -2 ‰.
iii. A decline of values is seen down to 14 m, albeit in the individual values for the profiles spanning a range of about 2 ‰
iv. There then follows an increasing trend, which persists in BH 13 down to its final depth of 22 m.

The inflection at the very top in the $\delta^{18}O$ - depth curve, proposed as typical of the near-surface evaporation/drying front (Allison et al. 1994; Barnes and Allison 1988), is not observed in any. There is a general decline in $\delta^{18}O$ values, the shapes of the observed curves placing them in the category of profiles characteristic of low recharge (Allison et al 1994).

7.2.4 *Deuterium*

Deuterium analyses were performed on samples at depth intervals of one metre for BH 13. The direct soil moisture reduction system functioned very well, giving excellent reproducibility for duplicate samples (see Table 11). Although the shape of the δD profile resembles that of $\delta^{18}O$ for depths below 4 metres, it appears quite different for the shallower samples. Figure 14 shows a plot of δD vs $\delta^{18}O$ for BH 13 with the world meteoric water line (WMWL) for comparison. From this it is clear that evaporation has influenced a number of the points. The deuterium excess d for all the samples in the profile is plotted against depth, along with other parameters, in Figure 9. Low values for d are seen particularly for the shallow samples, confirming the conclusion from the $\delta^{18}O$ data that the high values above some 6 m depth are due to kinetic evaporation. It has been remarked earlier that the classical evaporation front with its characteristic inflection is not visible in any of the profiles - albeit suggested in BH 12. Probably, the d values are produced by the process associated with such a front, but that repeated rapid infiltration events, which also appear to influence deeper sections of the profiles, distort the regular pattern such as observed by e.g. Allison et al. (1994).

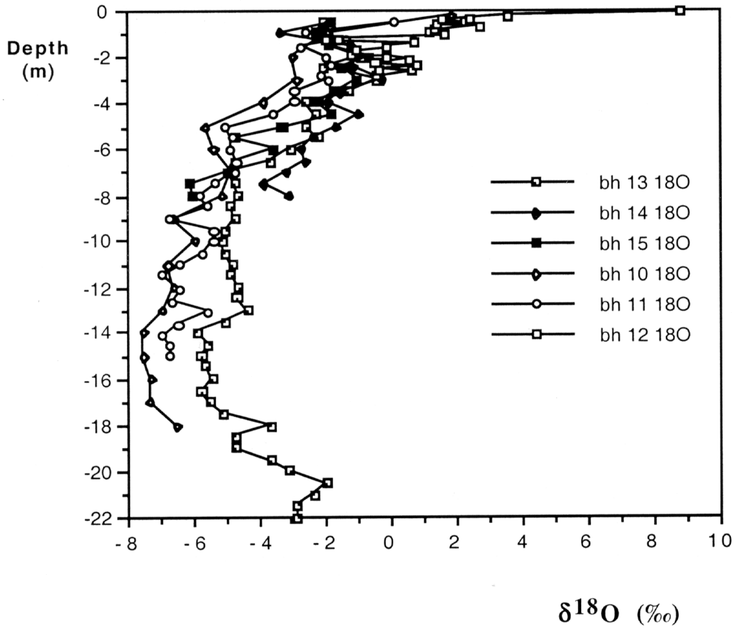


FIGURE 13

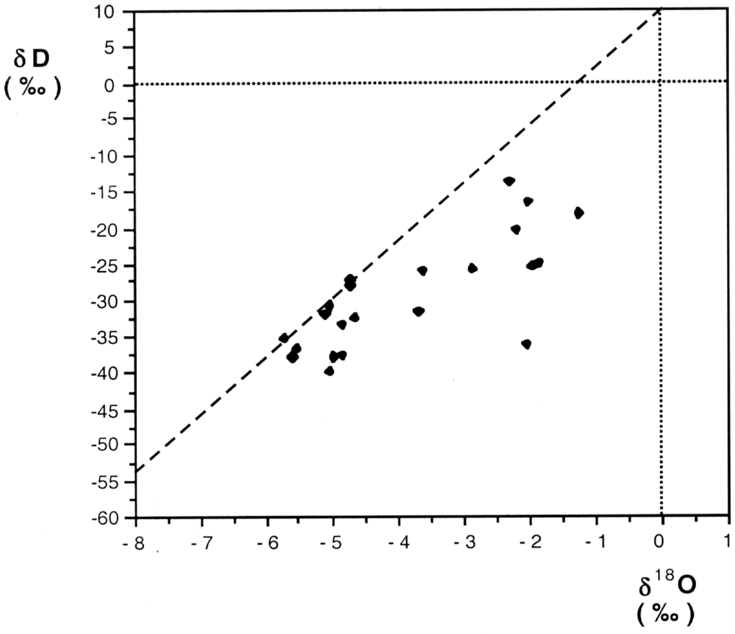


FIGURE 14

Table 11. Results for Deuterium Analyses

Sample Number	Normalised δ D (‰)	Average δ D (‰)
KSP 79	-16.8 -16.2	-16.5
KSP 81	-24.3 -25.3	-24.8
KSP 83	-36.2 -35.9	-36.0
KSP 85	-18.1 -18.3	-18.2
KSP 87	-14.0 -12.9	-13.5
KSP 89	-20.7 -20.2	-20.5
KSP 91	-32.0 -30.9	-31.5
KSP 93	-27.7 -28.3	-28.0
KSP 95	-33.9 -32.9	-33.4
KSP 97	-38.0 -37.6	-37.8
KSP 99	-39.9 -39.6	-39.7
KSP 101	-38.4 -36.4	-37.4
KSP 103	-31.9 -32.9	-32.4
KSP 105	-30.1 -31.5	-30.8
KSP 107	-35.8 -37.5	-36.6
KSP 109	-38.4 -37.4	-37.9
KSP 111	-34.9 -35.6	-35.2
KSP 113	-31.9 -31.8	-31.8
KSP 115	-26.9 -27.5	-27.2
KSP 117	-25.9 -25.9	-25.9
KSP 119	-25.4 -25.3	-25.4
KSP 121	-25.6 -25.9	-25.7

At greater depths, values for d then rise to around +10 ‰, confirming that these are associated with direct rainfall infiltration. Values of d drop somewhat near the very bottom of the profile. These are associated with an inflection in the $\delta^{18}O$ profile. This is tentatively interpreted as due to contamination of deeper auger samples by material from the near the top of the auger hole. Such contamination is not seen however in any of the other parameters measured for BH 13.

7.2.5 *Tritium*

The tritium results for BH 13 are given in Table 6 and plotted against depth in Fig. 9. On average, the values lie about 2 TU lower than those observed for BH 10 and the variations with depth are less pronounced. In neither case can the variations in tritium concentration be correlated with any of the other measured parameters.

8. RECHARGE ESTIMATES

8.1. Chloride concentrations

As there is no suitable time marker, such as a discernible tritium peak, no attempt was made to assess recharge by chloride balance for the entire moisture profiles. Recharge rate, or rather nett infiltration, was derived using the chloride mass balance equation:

$$C_P \, . \, P = C_R \, . \, R$$

where P is the precipitation, C_P the chloride concentration in rain, (about 1 ppm; Beekman et al. 1996), and C_R the chloride concentration in recharge. A mean annual rainfall of 336 mm is assumed (Table 3). The lowest chloride concentrations observed, and maximum recharge rate, are respectively:

BH 10 (1997) C_R = 200 ppm ; R = 1.8 mm a^{-1}
BH 13 (1998) C_R = 80 ppm ; R = 5.0 mm a^{-1}

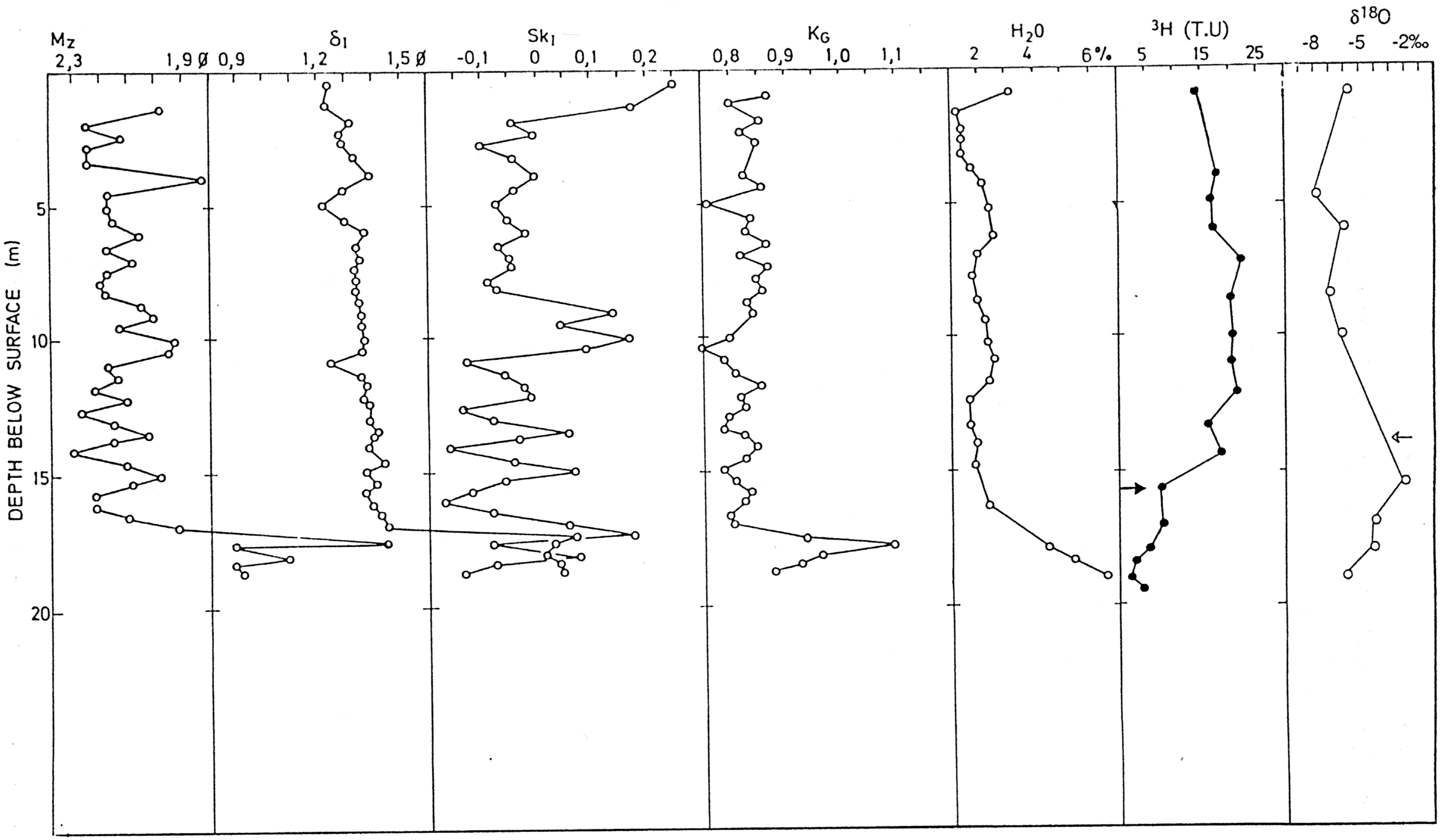
These figures reflect only the inferred downward movement of moisture as an equivalent water column in part of the profile, and set an upper limit to the inferred recharge rate to the underlying aquifer.

8.2 Tritium values

The result of zero TU for the control sample gives confidence that the tritium values measured in the deep profiles BH 10 and BH 13 are not influenced by any contamination in the laboratory. They both show that the moisture down to depths of 18 m to 22 m has a residence time of at most 3 tritium half-lives or 36 years. At a mean moisture content of 1.6 wt %, the equivalent water column to a depth of 22 m is 500 mm. Over a 36 year period this represents a recharge of some 4 % of annual rainfall, or some 13 mm a^{-1} for an average annual rainfall of 337 mm. Estimates of maximum recharge on the basis of chloride balance and assuming 1 mg L^{-1} of chloride in rainfall, lie in the range 1.8 - 5.0 mm a^{-1}. A more thorough analysis of the data may be required in order to understand this apparent discrepancy.

9. COMPARISONS WITH PREVIOUS STUDIES

As mentioned in the Introduction (Section 1.) several depth profiles were obtained at the Harefields site during an earlier project in 1977, down to depths of around 20 metres. The results for grain size analysis, moisture contents, tritium and $\delta^{18}O$ for BH 7, drilled during the 1977 study, are shown in Fig. 15.



Mean grain size, standard deviation, skewness, kutosis, moisture content, ^{3}H and ^{18}O concentrations for BH7. Closed arrow indicates bomb ^{3}H cut off. Open arrow marks estimated level of penetration of the 1973-74 heavy rainfall period from ^{18}O increase.

FIGURE 15

Whereas the moisture contents down to some 16 m is in the range of values observed in the 1997/98 profiles, there is a sharp increase up to nearly 7 % at the bottom of BH 7. This coincides with a sharp decrease in grain size, standard deviation, and excursions in skewness and kurtosis. No such rises in moisture content were observed in the 1997/98 profiles, which probably do not show such dramatic changes in grain size distribution. However, grain size information for BH 10-15 may elucidate some of the observed changes with depth, as well as position, of the different boreholes.

In 1977 tritium concentrations reached a high of some 22 TU at a depth of 7 m in BH 7, declining to about 2 TU near the bottom at 18 m. At the time, this was interpreted as the extent of the bomb tritium "peak". The leading edge of the exceptional series of rainfall years (1974-1977; Fig 5) was interpreted as the point of inflection in the $\delta^{18}O$ profile at some 16m.

During 1997/98 values of 5 to 8 TU were found at the maximum depths reached in BH 10 and 13. This suggests that the remains of the bomb peak have moved to greater depths. Rain for the 1995/96 period in which tritium concentrations in excess of some 5 TU were measured, may have penetrated to various depths in the profiles.

The minimum in $\delta^{18}O$ seen in various profiles obtained in the present project at depths around 14 m to 16 m, may possibly be correlated with the minimum around 5 m to 7 m in the 1977 profiles.

The large discrepancy in the recharge assessments based on the depth of post-bomb tritium levels on the one hand and minimum values of Cl^- concentration on the other, could possibly be explained by repeated invasions of rainfall through preferential flow to depths of 20 m or more, followed by periods of evapotranspiration, which build up the chloride concentration but cause losses of tritium.

10. CONCLUSIONS

1. Given the home-made augering equipment used, 22 m is the maximum depth to which it is reasonably possible to drill and sample reliably.

2. The direct equilibration method for measuring oxygen-18 in the moisture in soil/sand samples continues to produce good reproducibility. The choice of CO_2 for the equilibration is important in that the $\delta^{18}O$ value of the gas should be not too different from that of the moisture. Correction of values for different moisture contents seems to be possible.

3. The direct soil water reduction method using zinc metal for deuterium measurements gives excellent reproducibility.

4. Both the 1997 and 1998 profiles show remarkable differences in both absolute values and depth dependence of the parameters measured (moisture content, electrical conductivity, chloride concentration, oxygen-18, and tritium) even over a few tens of metres separation at both sites selected.

5. Conclusions regarding depth dependence and evaporative enrichment near the surface based on oxygen-18 values alone, have been fully corroborated by deuterium measurements.

6. Measurable, post-bomb tritium values are observed to the maximum depth in both of the deepest profiles. A careful laboratory assessment of a blank subjected to the same procedure as the samples, gives confidence in the results obtained. Using tritium as an indicator of depth of penetration with time, only a lower limit to the inferred recharge can be set.

7. There is a wide discrepancy between minimum recharge rates estimated on the basis of the tritium profiles and the lowest values of [Cl$^-$] observed. As yet, this discrepancy remains unresolved. A possible explanation would be repeated penetration of individual infiltration events to the depths attained by augering, and subsequent substantial water losses due to evapotranspiration.

8. The mechanism proposed under 7. might partially explain also the lateral and vertical variability of the other parameters measured. Grain size analysis is seen as important to remove the matrix factor from these variations.

9. The chloride concentrations for the three saturated zone water samples obtained in the area are nearly one order of magnitude below even the lowest values measured in the profiles. Therefore, it is concluded that either/or:

a) there should be deeper sections of the unsaturated zone in which the chloride concentrations are much lower than observed down to some 20 m
b) such infiltration as reaches the saturated zone, thereby constituting recharge, does so through bypass flow. This phenomenon was recognised early on by Smith et al. (1970) and has more recently been demonstrated by Beekman et al. (1996) in the unsaturated zone of a similar environment.

10. This Kalahari area can be regarded as a benchmark site on account of its relative accessibility, the wealth of information on the unsaturated zone obtained in this and earlier studies as well as the availability of detailed and ongoing local rainfall data.

ACKNOWLEDGEMENTS

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Chemical (Cl) and isotopic (^{18}O, ^{2}H, ^{3}H) study of the unsaturated zone in the arid region of Nefta (South Tunisia)

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Abstract. A chemical and isotopic study of the unsaturated zone in Nefta, southwestern Tunisia was initiated to gain an improved understanding of the recharge and evaporation processes in the shallow "*Continental Terminal*" (CT) sandy aquifer outcropping in the region of Nefta, which constitutes the most important water resource for agriculture and domestic uses in the region. A single 13.5-m core was extracted and subsampled from the unsaturated zone at the end of the "rainy season" (23-24 April 1998) using a hand auger to avoid fluid contamination. Estimated recharge rates based on isotope and chemical profiles, uncertainties, and recommendations for future research are discussed.

Introduction

The "*Continental Terminal*" (CT) sandy aquifer outcropping in the region of Nefta constitutes the most important water resource for agriculture and domestic uses. However, this aquifer has been undergoing, especially since the years 88, a drastic decrease in of its water table. Many little springs, which used to discharge about 800 l/s in the years fifties, and provide water for the whole oasis, have completely been drought during the last decade, due to the constant increase in of the water-well exploitation for agricultural purposes in the region.

Consequently, in order to assess the issue of sustainable water resources in the region, a comprehensive hydrogeological investigation program has been launched by the "*Commissariat Régional au Développement Agricole*" and developed in collaboration with the "Isotopic Laboratory at the Sfax National School of Engineering.

The chemical and isotopic study of the unsaturated zone in Nefta - part of the IAEA's RCP on "*Isotope based assessment of groundwater renewal and related anthropogenic effects in water scare areas*" - has been carried out within this general framework with the specific aim of getting a better understanding of the recharge and evaporation processes at the outcrop of the CT shallow aquifer.

1. General features

1.1. Location and climatology

The Nefta / Tozeur region (Djerid) is located in the South - Western part of Tunisia, on the northern side of the interior dry salty lake "Chott El Djerid" (fig.1). This region belongs to the arid zone of the country with an average mean precipitation of less than 100 $mm.y^{-1}$. As a consequence of this arid climate, there are no perennial rivers, and occasional superficial flows occur only during and after intense storms in the rainy winter season.

The long term pluviometric record registered at the climatologic station of Nefta (fig.2a) illustrates the high variability of the annual precipitation. These values may reach amounts superior to 500 mm in exceptional years (as in 1969), whereas dry periods are characterised by precipitation inferior to 30mm (only 23 mm in 70-71 "rainy season"!). The monthly distribution (fig.2b) shows that the main rain events may occur at any time, at the beginning or at the end, during the rainy season; between October and April (Moumni et Horriche, 1998).

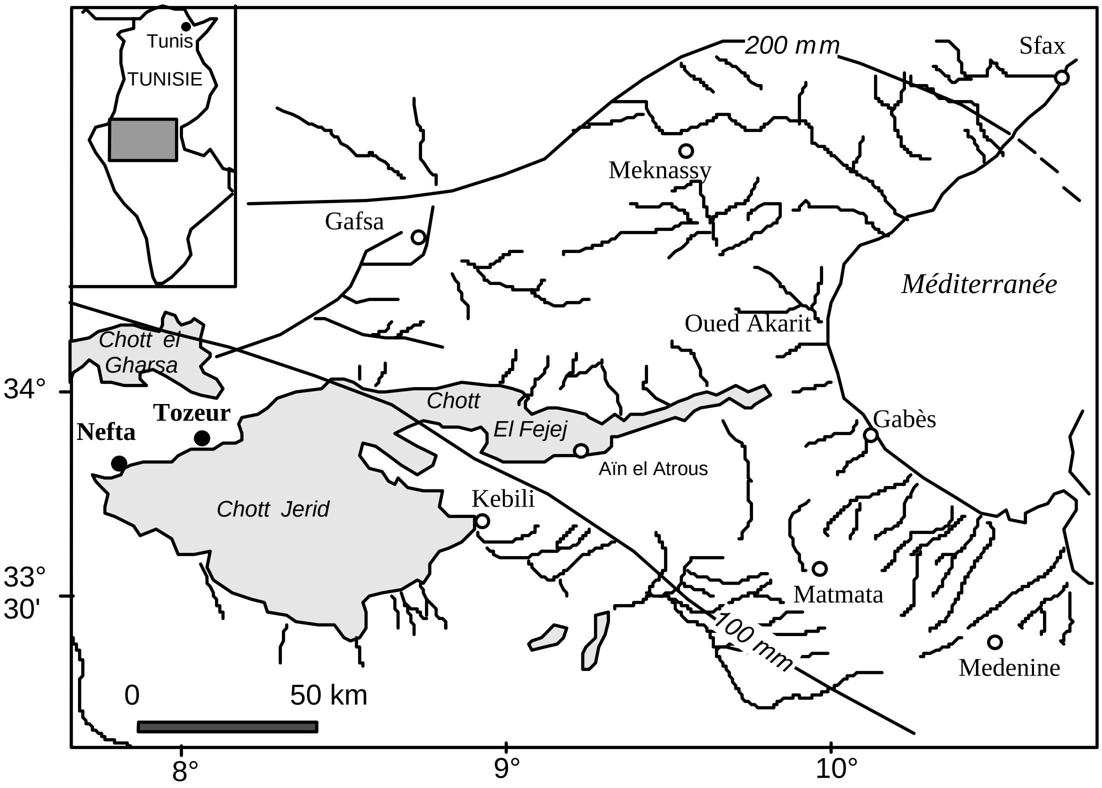

Fig. 1. location of the study area.

The influence of the frequent dry winds coming from the Southern Saharian regions, together with the high temperature all over the year (cf. table 1) result in a very high potential evaporation rate, much higher than the amount of precipitation during the same period (at the monthly scale).

In fact, the only possibilities of vertical infiltration of the rain events and actual recharge of the unconfined aquifers must be looked at the daily scale (rapid infiltration of the rain in very permeable sandy formations). The most favourable conditions to facilitate the infiltration consist in a sequence of a slight rain - to increase the permeability of the soil[1] - followed by heavier precipitation, possibly of several tens of millimetres in some days (a too high intensity is not favourable to the infiltration but concentrate the superficial flows).

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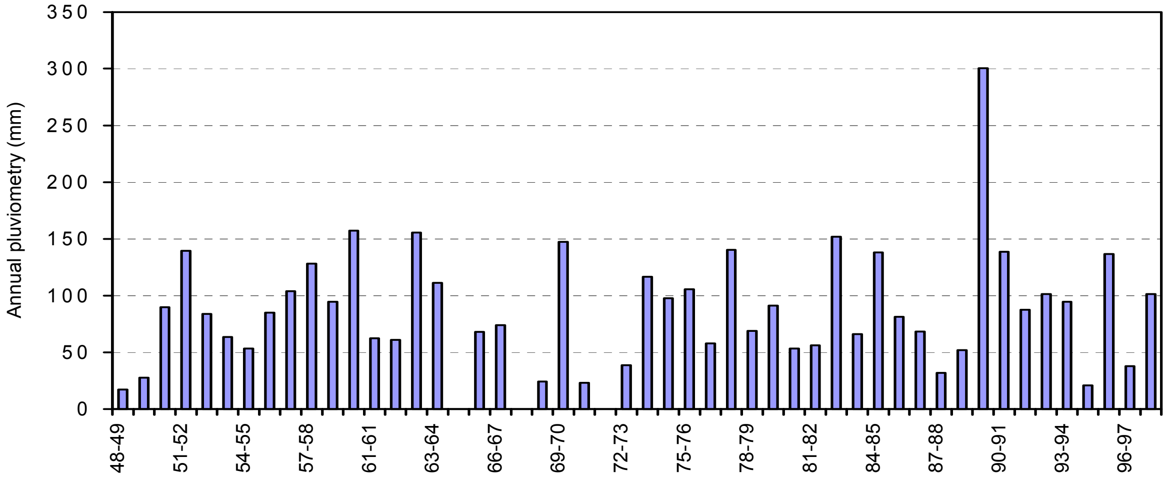
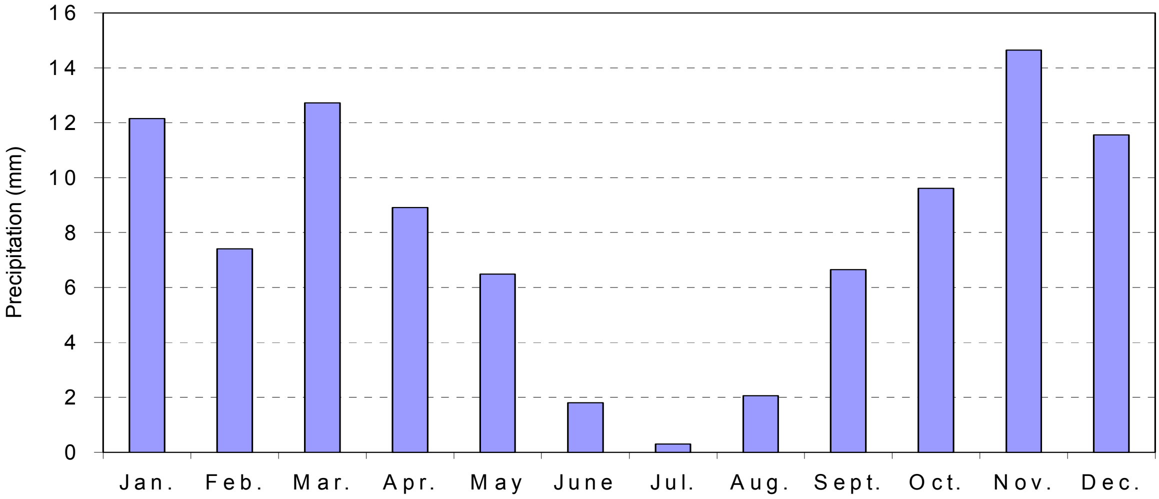
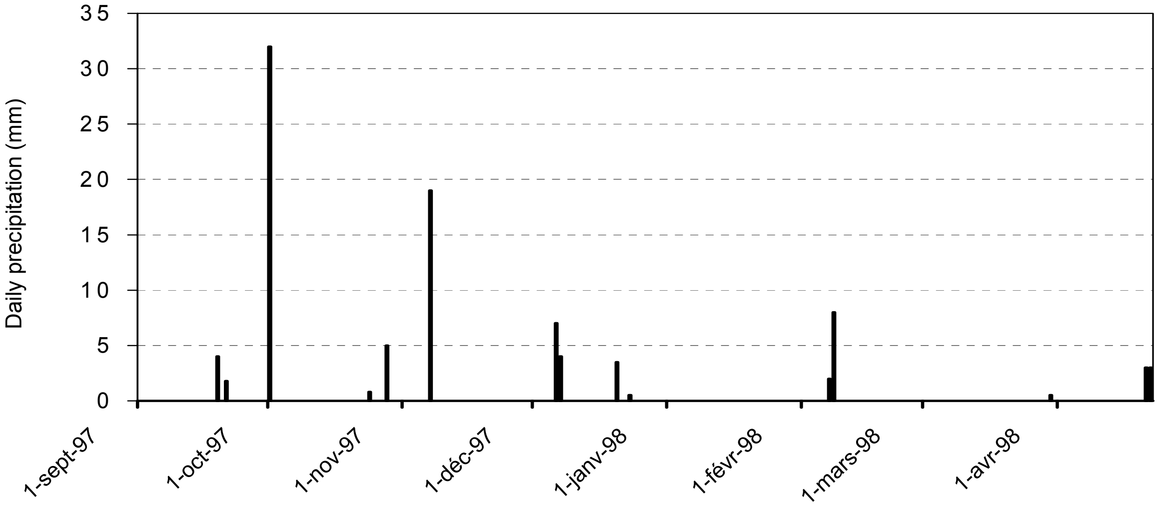
[1] A dry sand has a very low permeability and favours run-off



(a) Annual means.



(b) Monthly means (period 1950–1995).



(c) Daily precipitation during the 1997-1998 rainy season

Fig. 2 (a–c). Pluviometric records at the station of Nefta.

Table 1. Monthly mean values of the precipitation and the potential evaporation at the station of Nefta

(Temp.: period 1950-1995 ; Precip.: period 1950-1995 ; ETP: period 1984-1991)

	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**Total**
Temp	11.2	13.4	16.4	19.9	21.6	29.5	32	32.1	28.5	22.6	16.4	12	-
Prec.	12.15	7.41	12.72	8.91	6.49	1.8	0.3	2.06	6.65	9.61	14.65	11.56	**94.3**
ETP	50.28	65.17	101.1	142.3	188.9	227.4	258.2	227.9	163.8	133.3	67.2	49.2	**1675**

Daily measurements of the last rainy season concerned by the study (1997-1998) show (fig.2c) that some slight precipitation occurred late September (5.8 mm); these were followed by heavier rain beginning October (32 mm), which gave the possibility of effective infiltration during that month. The precipitation in November (19 mm) and December (15 mm) could also have, partially infiltrated. No infiltration may be expected from the following months, taking into account the low precipitation during the period January-April.

1.2. Geological setting and regional hydrogeology

The geological setting is constituted by a very thick sedimentary sequence starting from the Lower Cretaceous (Neocomian) to the Plio-quaternary deposits, with a stratigraphic gap between the Maastritchian and the Miocene (Mamou, 1990).

The study area corresponds to the outcrop of the "*Continental Terminal*" formation which appears in the centre of the East-West anticline uplift structure at the Northern side of the Chott El-Djerid along the Nefta - Tozeur axis (fig.3 ; fig.4).

The *Continental Terminal* aquifer is hosted in the Upper Cretaceous and Tertiary formations. According to the local structure and lithological characteristics, the main productive level are located either in the carbonated levels of the Turonian and upper Senonian in the carbonated levels of the upper Cenomanien, Turonnian and lower Senonian or in the Tertiary sandy formation (Pontian).

The South-West Tunisian region constitutes one of the natural outlet of the SSE-NNW regional flow which discharges mainly in the Chott Jerid (through the Mio-Plio-Quaternary sequence) and in the Chott El-Rhasa, on the other side of the Tozeur uplift.

More precisely, the area under study corresponds to the outcrop of the sandy Pontian formation where the natural outlet of the general deep CT groundwater circulation used to sustain a permanent discharge through the numerous springs located in topographic depression called "*Corbeille de Nefta*" (fig.4).

The chemical composition of the *Complexe Terminal* water, determined under the "*Corbeille de Nefta*" in the deep well "*Ras El Aïn*" is given on table 2.

Table 2. Chemical composition of the water in the Ras El Aïn deep well (N° IRH 20 786/5)

Ca	**Mg**	**Na**	**K**	**SO_4**	**Cl**	**HCO_3**	**Salinity**	**pH**
252	50	370	-	837	560	240	2520	8

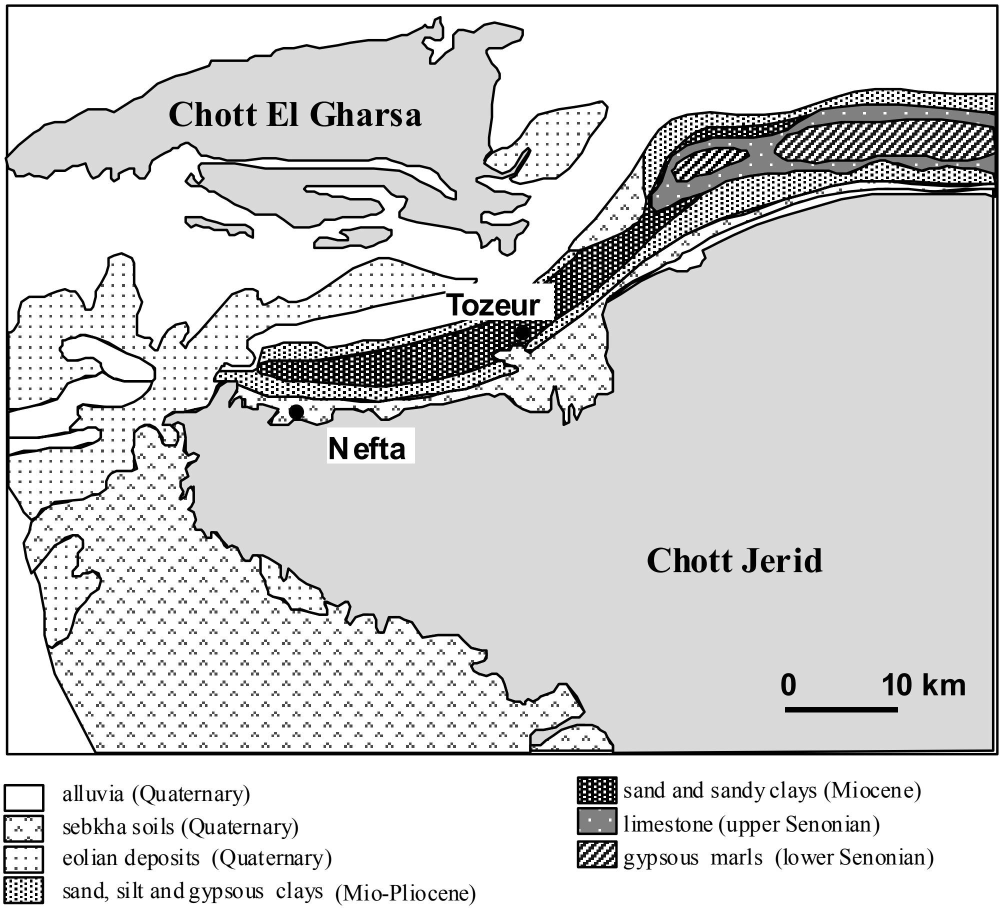


Fig. 3. Simplified geological map.
(Extracted from the geological map of Tunisia 1/500 000)

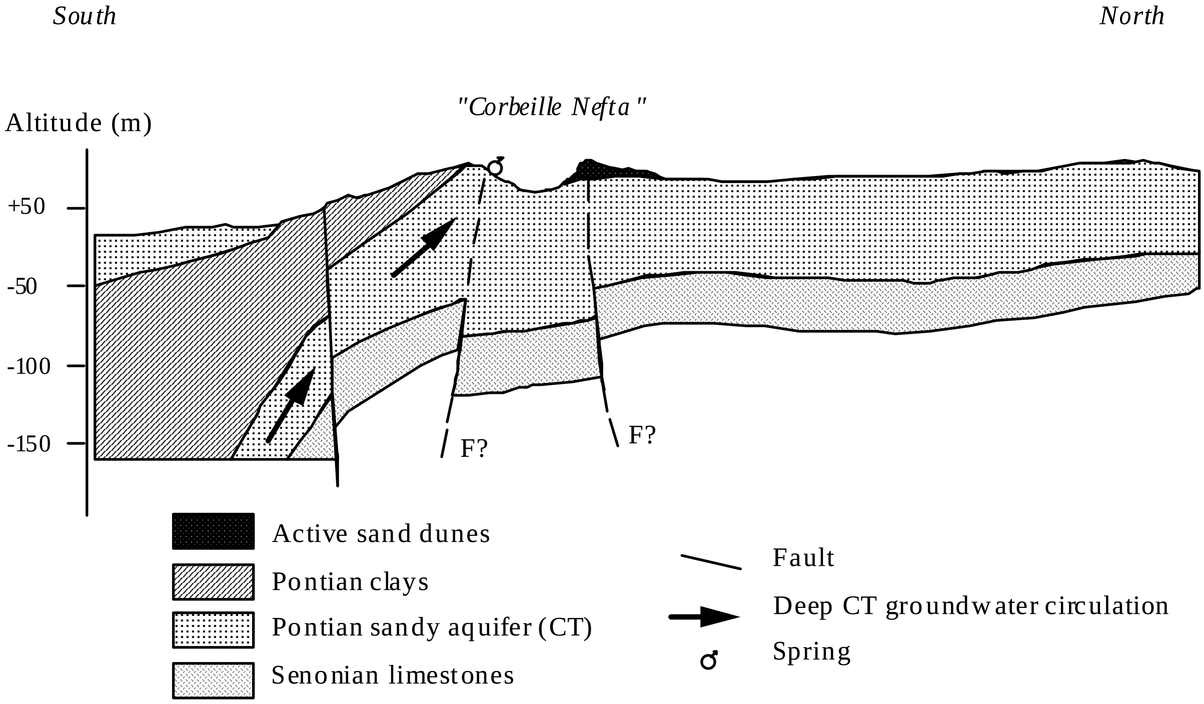


Fig. 4. Schematic geological cross section.

The isotopic content of the *Complexe Terminal* water varies with the position within the formation. In depth, its values range around –7‰ in ^{18}O (Jeribi, 1997). Concerning the aquifer in the Djerid study area, a compilation of analyses from waters sampled in the more shallow Pontian sands (Aranyossy & Mamou, 1985) has provided values in ^{18}O between -3.9 to -4.36 ‰ indicating a clear mixing with evaporated waters.

These isotopic characteristics, together with the carbon-14 activities of the dissolved carbonates have been interpreted by Mamou (1990) as an indication of present aquifer recharge on the outcropping Pontian aquifer in the Dräa Djerid. This present recharge is supposed to occur through two processes: one part from the "lateral infiltration" during the surface floods in the wadis ; the other part from the direct rain water infiltration into the permeable sandy formation. The ratio between these two parts is still unknown.

2. Sampling and analytical results

2.1. Sampling

The profile has been carried out at the end of the "rainy season" (23-24 April 1998) near the dry wadis in the small depression of Nefta ("Corbeille de Nefta"; fig.5). The coring was achieved using a hand auger (in order to avoid any risk of contamination by the fluid with a drilling machine). Samples were integrated between intervals of 15 cm from the topsoil to 60 cm depth; of 20 cm up to 5 m depth and 25 cm further down. Drilling was stopped at the depth of 13.5 m due to technical reasons.

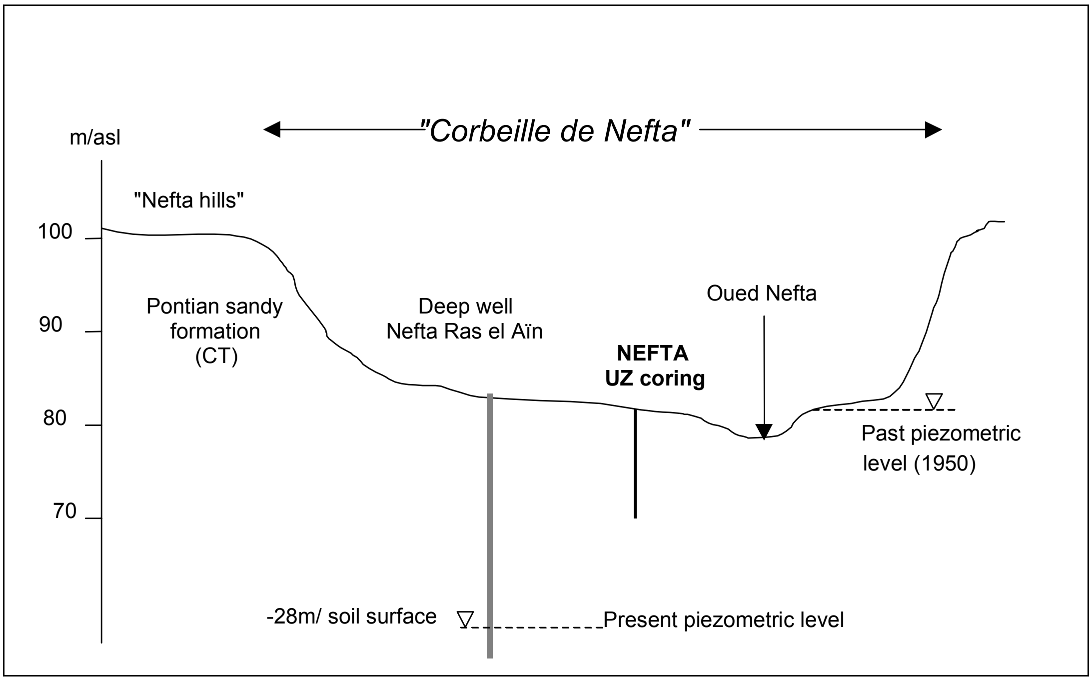


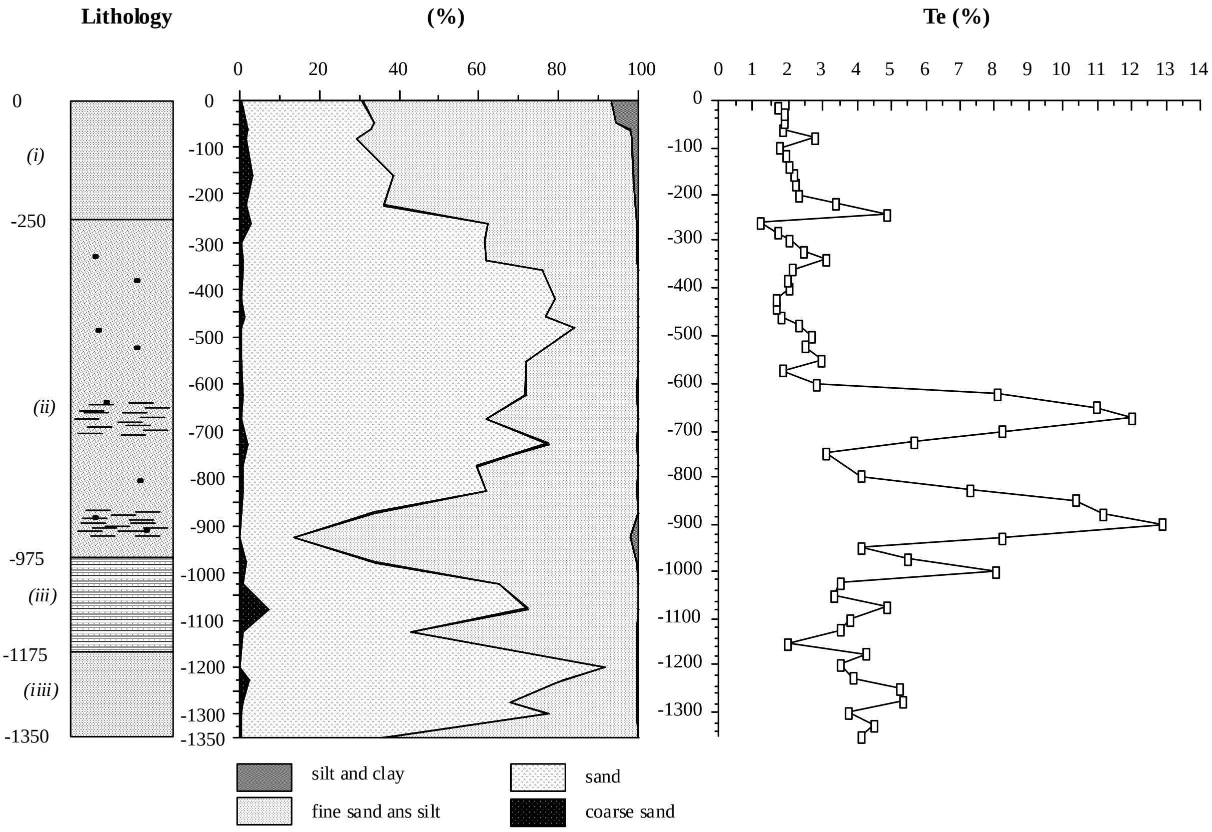
Fig. 5. Location of the coring in the depression of Nefta.

The soil samples were immediately conditioned in hermetic metallic boxes, to avoid any further evaporation to the sampling, and proceeded to the laboratories where the different operations and analyses have been carried out:

- at the ENIS; granulometry, water extraction by vacuum distillation, lixiviation, chlorine analysis (classical titrimetry, and HPLC for analysis of precipitation[2]) ;
- in the British Geological Survey (BGS) ; ^{18}O, ^{2}H analyses on the extracted water samples ;
- in the IAEA laboratories in Vienna ; tritium measurements (by direct counting).

- **lithological profile** (fig.6a) **and granulometry** (fig.6b)

The core is formed by a succession of sandy strata with small intercalation of more silty layers.
Two more permeable strata, corresponding to the more sandy parts in the profile correspond to the sectors ; 2.5 to 8 m and 11 to 13 m. An intercalation of more silty layers appears around 9 m and 11 m depth.



(i): fine sand with small roots
(ii): coarse to medium size sand with quartz and some silty clayey levels
(iii): sand with small clay layers
(iiii): coarse to medium size sand

Fig. 6. NEFTA UZ profile: physical characteristics.

2.2. Analytical results

All the results are presented on table 3, together with the corresponding analytical uncertainties, when available. Precision on ^{18}O and ^{2}H measurement are of 0.1 and 1‰ respectively.

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[2] HPLC: High Performance Liquid Chromatography

Table 3. Analytical results

Z1 *(cm)*	**Z2** *(cm)*	**Hp** *%*	**Hv**	**Cumul** *(mm)*	**Cl** *(mg/l)*	**Cl cumul** *(g/m^2)*	**Cl th. Age** *(years)*	**O-18** *(‰)*	**Deut.** *(‰)*
0	-15	1,70	0,023	3	2723	9	14	0,8	-19
-15	-30	1,90	0,026	7	3050	21	31	0,1	-27
-30	-45	1,91	0,026	11	1498	27	40	-0,5	-22
-45	-60	1,87	0,025	15	2696	37	55	-2,6	-37
-60	-80	2,78	0,038	22	3054	60	89	-4,4	-40
-80	-100	1,77	0,024	27	1850	69	102	-4,5	-47
-100	-120	1,97	0,027	33	830	73	109	-4,7	-49
-120	-140	2,08	0,028	38	432	76	112	-4,9	-53
-140	-160	2,14	0,029	44	2036	87	130	-4,3	-48
-160	-180	2,21	0,030	50	6819	128	190	-3,4	-46
-180	-200	2,29	0,031	56	2275	142	211	-3,5	-43
-200	-220	3,38	0,046	65	2620	166	246	-5,6	-51
-220	-240	4,90	0,066	78	3888	218	322	-6,1	-50
-240	-260	1,19	0,016	82	5687	236	349	-0,5	-30
-260	-280	1,70	0,023	86	5545	261	387	-3,2	-41
-280	-300	2,07	0,028	92	2957	278	412	-2,5	-32
-300	-320	2,44	0,033	98	2066	291	432	-3,8	-37
-320	-340	3,07	0,041	107	1829	307	454	-4	-39
-340	-360	2,10	0,028	112	2714	322	477	-4,2	-39
-360	-380	2,01	0,027	118	3422	341	505	-2,8	-34
-380	-400	2,04	0,028	123	2001	352	521	-5,1	-40
-400	-420	1,66	0,022	128	3043	365	541	0,9	-20
-420	-440	1,66	0,022	132	1481	372	551	0,7	-21
-440	-460	1,80	0,024	137	909	376	557	-2,6	-38
-460	-480	2,30	0,031	143	1062	383	567	-0,9	-31
-480	-500	2,67	0,036	151	1623	395	585	2,3	-12
-500	-525	2,52	0,034	159	762	401	594	-0,6	-22
-525	-550	2,99	0,040	169	889	410	607	-2,5	-37
-550	-575	1,84	0,025	175	959	416	616	-1,6	-27
-575	-600	2,85	0,038	185	426	420	622	-2,9	-42
-600	-625	8,09	0,109	212	426	432	640	-4,6	-41
-625	-650	10,98	0,148	249	405	447	662	-5,5	-52
-650	-675	12,00	0,162	290	735	476	706	-5,2	-48
-675	-700	8,20	0,111	318	575	492	729	-3,8	-39
-700	-725	5,70	0,077	337	737	507	750	-4,5	-46
-725	-750	3,09	0,042	347	1176	519	769	-3,6	-37
-775	-800	4,13	0,056	361	934	532	788	-3,8	-35
-800	-825	7,30	0,099	386	761	551	816	-3,3	-39
-825	-850	10,37	0,140	421	740	577	854	-4,5	-43
-850	-875	11,18	0,151	459	898	610	904	-4,7	-45
-875	-900	12,90	0,174	502	478	631	935	-4,4	-48
-900	-925	8,21	0,111	530	1034	660	978	-4,6	-49
-925	-950	4,12	0,056	544	1395	679	1006	-3	-32
-950	-975	5,49	0,074	562	987	698	1033	-3	-33
-975	-1000	8,03	0,108	589	239	704	1043	-4,2	-37
-1000	-1025	3,50	0,047	601	2408	732	1085	-5,3	-44
-1025	-1050	3,34	0,045	612	640	740	1096	-4,3	-38
-1050	-1075	4,91	0,066	629	730	752	1114	-2	-32
-1075	-1100	3,84	0,052	642	901	763	1131	-3,2	-47
-1100	-1125	3,52	0,048	654	2347	791	1172	-1,1	-31
-1125	-1150	2,00	0,027	661	713	796	1179	-1,9	-39
-1150	-1175	4,25	0,057	675	282	800	1185	-4,9	-46
-1175	-1200	3,50	0,047	687	172	802	1188	-5,4	-51
-1200	-1225	3,91	0,053	700	266	806	1194	-4	-43
-1225	-1250	5,24	0,071	718	263	810	1201	-6,5	-58
-1250	-1275	5,36	0,072	736	514	820	1214	-5,8	-47
-1275	-1300	3,78	0,051	748	654	828	1227	-6,1	-48
-1300	-1325	4,50	0,061	764	245	832	1232	-5,3	-46
-1325	-1350	4,10	0,055	777	292	836	1238	-3,3	-37

Z1-Z2: interval of sampling ; Hv: volumetric humidity ; Cl th Age: Cl theoritical age (years) ;
Hp: weighted humidity ; Cumul: cumulative water content

Due to the low humidity, the tritium counting has been made on grouped soil samples representing wider intervals than the other measurements (table 4)

- **Water content** (fig.6c)

The water content has been obtained on the same samples extracted by vacuum distillation and further checked by over desiccation at 110°C (during 12 hours).

The superficial level, formed by loamy sands about 2.5 m in thickness, shows a slight progressive increase of the water content from 1.7 % in weight (corresponding to about 2.3 % volumetric[3]) to 2.2 % (~2.9 % volumetric). The only point above the general trend in this superficial stratum (2.8 % at 70 cm depth) corresponds to a level marked by the presence of organic matters (presence of small roots).

The first sharp increase in water content is located at the bottom of the superficial sandy formation, just before the interface with the underlying layer. This increase in humidity may correspond to the change of permeability between the two layers (the "yellow sands" below being more permeable than the upper superficial formation).

Below that transition, the increase in water content does continue regularly up to 6 m in depth where two very sharp peaks (maximum at 6.8 m and 8.8 m) are marking the presence of two clayey layers at the same depth.

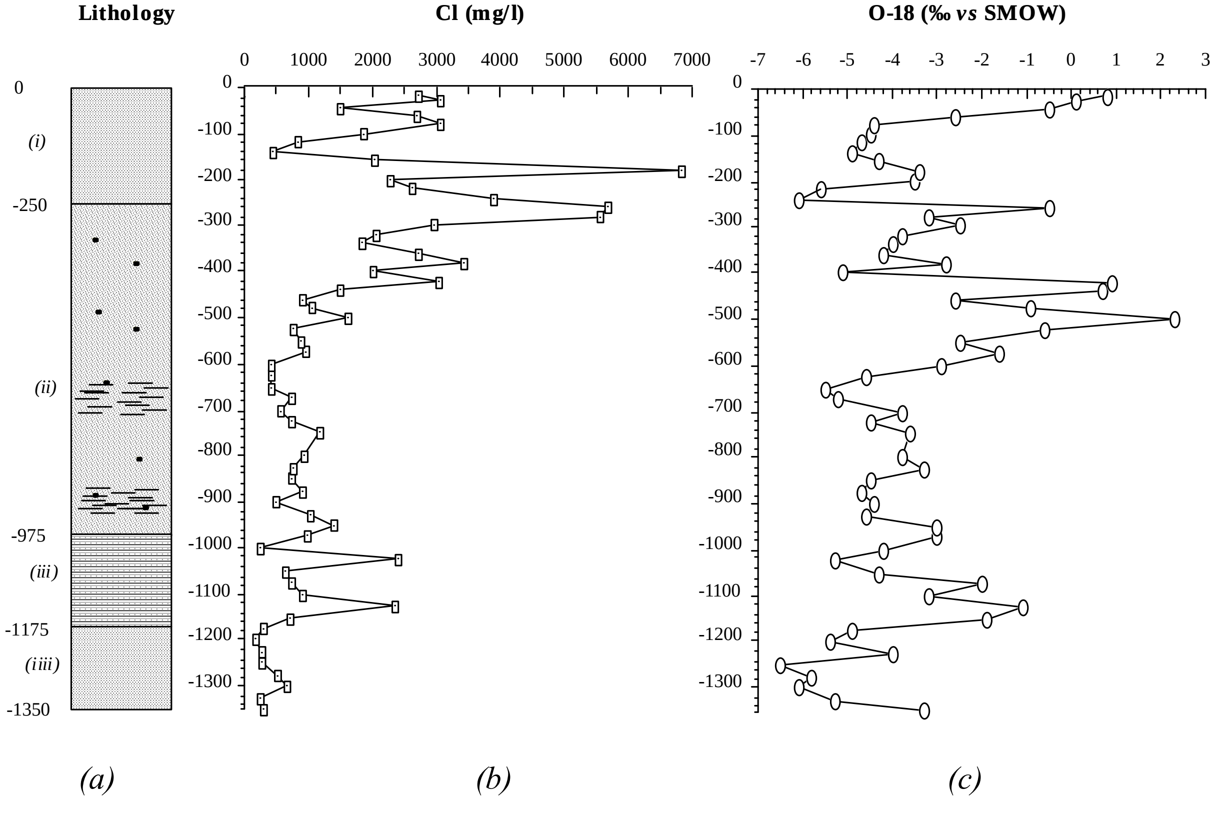

Fig. 7. NEFTA UZ profile: Chemical and isotopic results.

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[3] *The humid bulk density is estimated, by comparison with measurements made on other sites, to be between 1.20 and 1.4.*

- **Chlorine profile** (fig.7a)

The chlorine profile is mainly characterised by two different sections:

- The upper part, from the surface to 1.5 m in depth, with a global decrease in the concentration, ranging from 3000 ppm at the top to less than 500 ppm at the bottom;
- The lower part, starting with an important chorine peak located at 2 m in depth (of about 7000 ppm), shows a progressive decrease in the concentration with depth to reach a quasi "steady state" of some hundreds ppm (300 to 500) below 12 m.

  These values are, although slightly less concentrated, in the order of magnitude than those measured in the aquifer (cf. chap 2)

  However, it should be noticed that the water representative of in the aquifer was sampled at about 40 m in depth, then quite much deeper than the lower part of the profile. In fact, the isotopic and chemical concentration of the profile between these two levels is supposed to be more or less in a "steady states" around theses values. But the verification of this hypothesis could only be made through the realisation of a deeper coring.

- **Stable isotopic profile** (fig.7b and 7c)

The stable isotopes analysis (^{18}O and ^{2}H) of the interstitial water seems - at first glance - to - show a much more variable (or even erratic !) results than the chlorine profile. However, the same global tendency can be evidenced:

- The upper part of the profile (0 - 1.5m) corresponds to a regular decrease in stable isotopic content ; from the enriched value at the surface (+ 1‰ in ^{18}O, obviously due to the evaporation) and the depleted value at the 1.5 m depth (-5‰ in ^{18}O).
- The lower part of the profile (below 1.5 m) shows a succession of enrichment peaks followed by a progressive decrease in stable isotopic content to reach a minimum value around –6.5‰. In more detail, four sections can be distinguished in this part:
  (1) from 1.5 to 6 m, important variations in the isotopic content (-6‰ to +2.5‰ in ^{18}O) corresponding to the succession of well defined enrichment peaks ;
  (2) from 6 to 10 m, a more regular part with concentration ranging between -5 ‰ to -3‰ in ^{18}O ;
  (3) from 10 to 12 m, a small enriched peak (-1‰ in ^{18}O) ;
  (4) below 12 m, very depleted values (up to –6.5‰ in ^{18}O).

The deuterium profile (not represented in the report) shows the same tendencies as the O-18.

Tritium profile (fig.8)

The tritium profile shows variations in tritium concentration between O and 15 TU (table 4). A general trend of decreasing the activity with depth (up to 12 m) can be drawn, before the presence of a little "peak" (10 TU) at 12.5 m. However, it should be already underlined that there is great uncertainty on these values (many of them are under the analytical precision threshold), which reduces the confidence in interpretation.

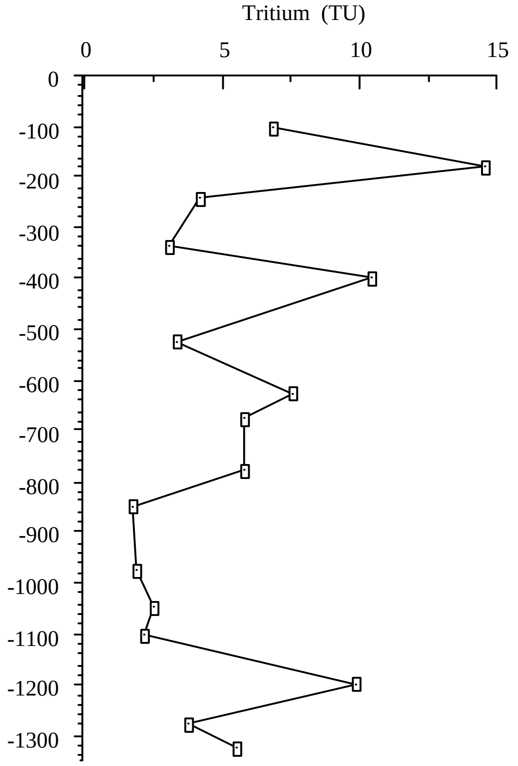

Table 4

P (cm)	TU	Error
80-140	6,91	4,50
140-200	14,59	4,63
220-240	4,3	4,46
320-340	3,14	4,44
360-400	10,48	4,55
480-525	3,43	4,44
525-625	7,63	4,51
650-675	5,89	4,48
725-775	5,89	4,48
825-850	1,84	4,42
950-975	1,98	4,42
1025-1050	2,56	4,43
1075-1100	2,27	4,42
1100-1200	9,95	4,55
1225-1275	3,86	4,45
1275-1325	5,58	4,53

Fig. 8. Tritium profile.

3. Discussion and interpretation

- **Water content**

It is noticeable that, though the profile was made at the end of the rainy season, the water content is very low at the surface of the soil. This feature illustrates the efficiency of the evaporation and also corresponds to the fact that the main rain events occurred at the beginning of the 97-98 rainy season (cf. fig.2b and 2c). The period of several months, elapsed between these rain events and the sampling, was long enough to allow the uptake by evaporation of most of the infiltrated water.

As a matter of fact, the profile seems to be characterised by a general trend - corresponding to a regular and slight increase in the humidity with depth (of about 0.17% per meter) – affected by picks due to changes in the lithology (presence of argillaceous layers, interfaces or presence of organic matter).

This general trend may reflect the establishment of a "*long term evaporative profile*" locally modified by slight infiltration events and lithology influences (presence of “low mobile” interstitial water in more clayey layers).

Compared to the amount of water stored in the profile and the general knowledge of the infiltration under arid conditions (Aranyossy, 1978 ; Zouari, 1983 ; Yousfi, 1984) it can be assumed that the last rainy season 97-98 concerned by the profile has penetrated into the soil up to the minimum depth of about half a meter. That would correspond to a minimal amount of water of 15 mm (*i.e.* about 16 % of the water precipitated in the region). This percentage of rain water remaining in the soil, estimated at the end of the “rainy season”, will of course drastically decrease until the end of the dry season (April to September).

- **Chemical and isotopic tracers**

Both chemical (Cl) and isotopes (^{18}O, ^{2}H) evolution in the upper part of the profile, suggest that the evaporation, starting from the last rainy season (between January and April 98) before sampling**,** affects at least the first metre of the soil.

Between 1.5 and 6 meters depth, the profiles are still marked by longer term evaporation effects which globally correspond to a section enriched both in chlorine and heavy isotopes. This general evaporation profile is perturbed by infiltration events characterised by lower values in chlorinity and stable isotopes, and pushed downwards by successive “piston flow” mechanism.

Below this section, the three different parts described in the profile (cf. 2) may be interpreted as follows:

- From 6 to 10 metres; the almost “steady-state” section (both in isotopes and chlorine) corresponds to the bottom of the regular evaporation profile (cf. fig.7). The ^{2}H / ^{18}O plot (fig.9) which shows an evaporation line ($\delta^2H = 4.5 * \delta^{18}O - 24$) defined with a quite good correlation ($r^2 = 0.8$) supports this argument.
- From 10 to 12 meters, the more clayey sandy layer - less permeable than the other layers and significantly marked by higher chlorine and heavy isotopic content - seems to refrain, somehow, the infiltration which occurred occasionally in the superficial layers,
- Below 12 m, the lower part of the profile, with the lowest content in chlorine and the more depleted in heavy isotope, move closer to the local composition of the *Complexe Terminal* water, suggesting a higher contribution of this water coming from the deeper parts of the aquifer.

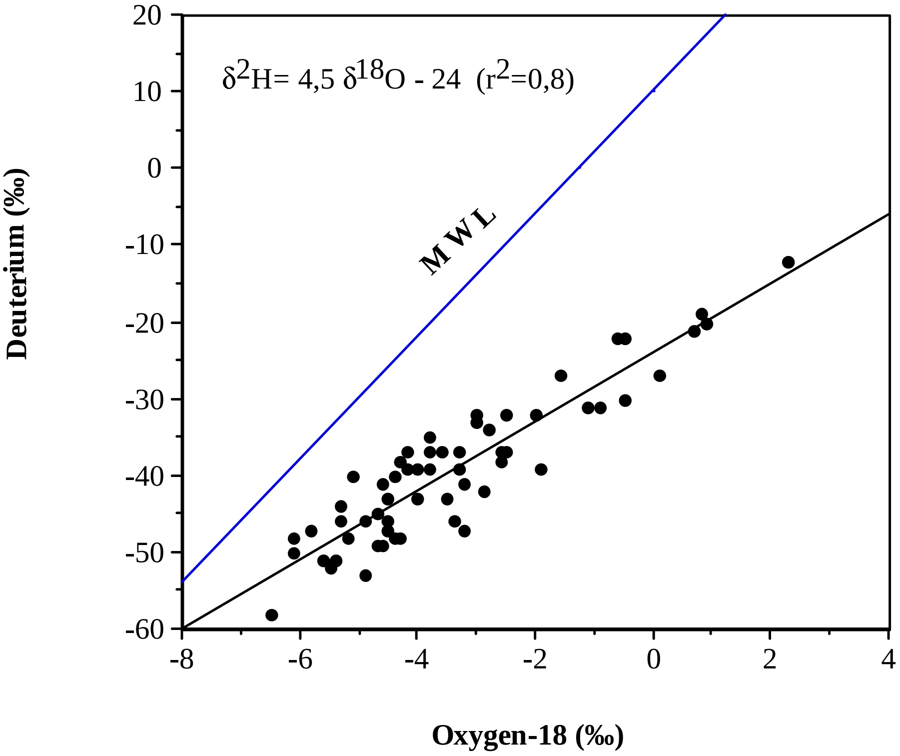

Fig. 9. Deuterium / Oxygen-18 plot for the all set of sample of the Nefta UZ coring.

The alternation of infiltration events and evaporation processes marked by the isotopic and chemical profile seems compatible with the hypothesis of local present aquifer recharge suggested by Mamou (1990). The presence of tritium activity in the profile, although difficult to interpret quantitatively, is also consistent with this hypothesis.

In these conditions, the chlorine concentration profile should theoretically provide a tool for a quantitative estimate of this recharge. Taking into account a local rainfall input of about 7mg.l^{-1}, an application can be attempted for different parts of the profile:

- 1 - 1.5m: Ci = 1500 ppm
- 1.5 - 4.5m : Ci = 3500 ppm
- 4.5 - 10 m:Ci = 750 ppm

Ci being the chlorine concentration in the profile.

Applying the classical formulation: R = Cp * P / Ci ; where Cp is the chlorine concentration in precipitation, P the average precipitation, the theoretical recharge rates are respectively:

- 1.0 - 1.5 m: 0.45 mm.y^{-1}
- 1.5 - 4.5 m : 0.19 mm y^{-1}
- 4.5 - 10 m:0.9 mm.y^{-1}

In terms of paleo-recharge, the application of the classical equation (Edmunds et Gaye, 1994):

$$t = \int_{z=0}^{Z=13.5} Cr * \theta * dz \ / (Cp*P)$$

would provide the theoretical residence time of the chlorine given in table 3 (Column "Cl theo. age"). In this calculation, based on the total amount of chlorine stored in the profile and the assumption of a constant value of the term Cp*P, the "Cl age" (which should also correspond to the “age” of the water recharge at the same depth) would be of more than 600 years at 6 meters depth.

In our case, these values seem to be over-estimated because of:

- the under-estimation of the input value of annual chlorine content in the profile. In fact, the area being rounded by several big saline dry lakes (sebkha and Chott El-Jerid, El Gharsa, El-Fedjej…) as important amount of salt is taken out by the winds during the dry season and spread on the soil all over the region ;
- the frequent presence of evaporites (gypsum often associated with NaCl) in the soils themselves, which leads to an over-estimation of the Ci value.

Consequently, great care should be taken in applying the Cl methodology in this region to get reliable quantitative estimate of the infiltration.

In semi-quantitative interpretation of the stable isotopic profile and chlorinity profile it can be attempted assuming a piston flow model pushing downwards the successive infiltrated “trenches“ of partially evaporated water of the successive rainy season. In that case, a sequence of about 10 years could be distinguished in the first 6 meters of the profile. Taking into account the total amount of water in the profile (about 185 mm), that hypothesis would correspond to an infiltration rate of about 18.5 mm.y^{-1}.

In conclusion, it seems that the simple application of the "chlorinity equation" may lead to an under-estimation of the recharge through the sand dunes. On the other hand, the approach based on the comparison between chlorine and isotopic profile seems to provide an over-estimate of the recharge.

A possible validation of the methodology would certainly consist in the realisation of chronological sequence of several profiles at the same site in order to follow the displacement of the isotopic and chlorinity peaks under the influence of an infiltration event. One efficient sequence could be: one at the end of the dry season (beginning September), one in the middle of the rainy season (January), at the end of the rainy season (April) and another profile at the end of the following dry season.

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The use of unsaturated zone solutes and deuterium profiles in the study of groundwater recharge in the semi-arid zone of Nigeria.

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Abstract. Two unsaturated zone profiles (MF and MG) in NE Nigeria have been sampled for inert tracers (Cl, Br, NO_3 and δ^2H to investigate recharge rates and processes. The upper MF and MG profiles have sandy lithology, lower moisture content (<5%), low conservative solute concentrations and δ^2H around -30‰. All these indicate that present day recharge is taking place. The lower section of the MF profile shows a distinct contrast with high moisture content (up to 27%), very high chloride (average 2892 mg/L) and relatively enriched deuterium (-12‰), indicating the effect of evaporative enrichment. This lower section corresponds to low permeability lacustrine deposits probably representing the former bed of Lake Chad where little or no infiltration has been occurring since the mid-Holocene when the lake extended over this area. The sand-covered areas of the Sahel of the NE Nigeria provide an important phreatic aquifer. An estimation of the amount of recharge using the unsaturated zone chloride mass balance gives significant rates of 14 mm/a and 22 mm/a for the upper MF and MG profiles respectively. These rates mainly span the period of the recent Sahel drought and even higher recharge rates may occur during wetter periods. These rates fall within the 14 mm/a to 53 mm/a range estimated for the Manga Grasslands area in the NE Nigeria obtained in an earlier study. From the water resource point of view, the region has potential for perennially-recharged groundwater resources that can sustain the present abstraction level which is mainly via dug wells.

1. Introduction

A rational approach to groundwater resources management and development requires knowledge of the origin of the resources and especially of their replenishment. This information represents basic input data for quantitative modelling, which increasingly is being used as a tool for groundwater management practices. The estimation of the amount of recharge is fundamental for a sustainable management of groundwater resources. This is extremely important especially in semi-arid and arid regions where surface waters are either seasonal or non-existent, and groundwater becomes the perennial source of water supply. The use of solutes in conjunction with isotope methods provides a powerful tool for the investigation both of modern hydrological processes and to reconstruct palaeohydrology. Recent reviews of techniques for estimating groundwater recharge [1, 2 & 3] emphasise the value of chemical and isotopic methods, especially in semi-arid zones.

The present study area is situated in the northeastern part of Nigeria, north of latitude 12°00’N (Fig. 1), and is mainly characterised by low rainfall (<500 mm) and high evaporation rate (>2000 mm). The landscape is characterised by sand dunes of different ages [4] and interdunal depressions. The loose sandy surface cover shows no runoff and supports annual grasses, shrubs and occasional trees. However, the interdunal depressions are moderately vegetated, but at the fringes of playa lakes are densely vegetated with doum palm, date palm, acacia and cultivated crops. Two sites (Malam Fatori and Magumeri) were selected to carry out unsaturated zone profiles (Figure 1). The Malam Fatori site has a series of prominent and

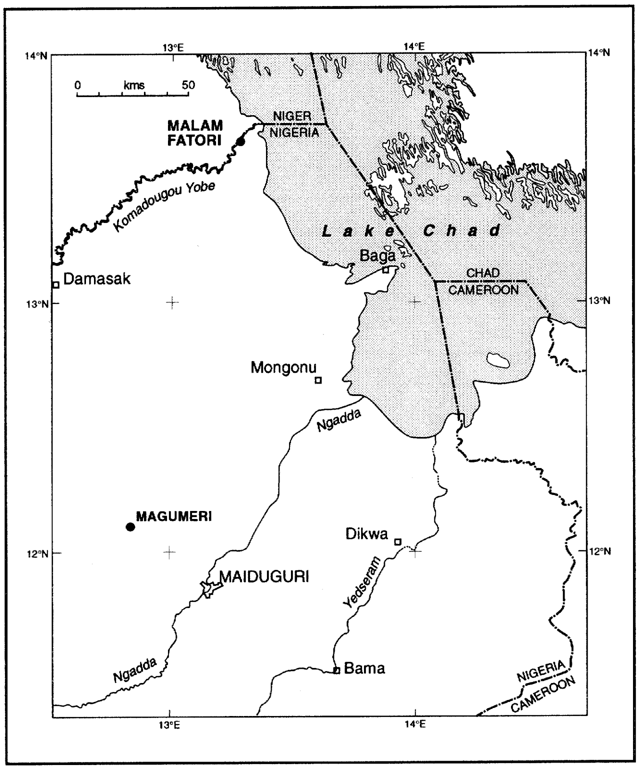

Fig. 1

relatively stable dunes, which form domes that probably represent past barchanoid dunes, and undulating sandy flatlands. Vegetation in this site is composed of annual grasses and shrubs. The Magumeri site shows a more stabilised longitudinal dune with axis trending in NE-SW directions. It is also characterised by annual grasses, shrubs and few tress. The dune sands are composed of quartz and feldspar with minor mica, while the depressions are composed of fluvio-lacustrine clays. The sediments of the dunes and depressions constitute the superficial deposits lying on top of the Quaternary Chad Formation, the youngest stratigraphic formation of the Chad basin. These superficial deposits provide an important phreatic aquifer that supplies perennial groundwater resources to a number of communities via dug wells. However, the local people have observed declines in the water table, and this has raised questions on the overall sustainability of the resource.

The aim of this paper is to present results of recharge estimation using inert chemical and isotopic tracers from these two unsaturated zone profiles in NE Nigeria.

2. Methodology

Hand augering was used to drill two profiles to an average depth of 16 m. One site (MF) was at Malam Fatori (13°39.02’N & 13°20.03’E). The second site (MG) was at Maigumeri (12°05.92’N & 12°49.06’E) MG. Samples were collected at intervals of 0.25 m for the first 10 m and then at 0.50m to the total depth of the profiles. Samples were homogenised over the interval in a thick nylon bag and subsampled into glass Kilner® jars, which were then sent to the BGS laboratory in UK for analysis. Moisture contents were measured gravimetrically. Subsamples of the field-moist sand were processed by elutriation using deionised water (30 ml deionised water added to 50 g of soil sample). Chloride, bromide and nitrate concentrations were determined by automated colorimetry. Deuterium content was measured by direct reduction of the soil sample over zinc shot [5].

Groundwater samples were also collected in 60ml Nalgene9 bottles from the shallow phreatic aquifer and the deep confined aquifer. All samples were analysed at BGS for inorganic analysis by ICP-OES and automated colorimetry.

3. Results

Two meteorological stations (Kaska and Garin Alkali) in the area have been used to obtain annual amounts and chloride concentrations in rainfall for the period 1992-97 and these results are described in greater detail [6]. The results from these stations were used to obtain a mean rainfall amount of 389 mm/a and mean weighted chloride of 1.7 mg/L for the study area. These form input data for the estimation of groundwater recharge using the chloride profile technique.

The MF profile shows variable lithology and texture (Fig. 2), with fine sand at the top 3 m, changing to silty clay, and clay with bands of silt to the total depth of the profile. The water table was not reached because of difficulty in drilling through the plastic clay encountered at 13 m up to 16 m, using the manual hand auger. The total depth of the profile is 16 m. From the data of nearby wells the water table is at a depth of 21 m. The moisture content in MF shows distinct variability that reflects the changes in lithology and texture (sand to clay), and ranges from 2% to 27%. The chloride results obtained by elutriation are given together with Br, NO_3 and δ^2H in Table 1. In this profile a clear hiatus can be seen at about 3m depth, shown by the moisture content which marks the transition from sandy lithology to clays, as well as by the discontinuity in Cl and δ^2H. Concentrations of chloride have a mean value of 47 mg/L Cl in the upper 3m but in the lower clay sequence the mean Cl concentration is 2892 mg/L (Table 2). The δ^2H values in the upper profile ranges from –27‰ to –39‰ with an average of –30‰. These are also lighter than in the clays in which δ^2H ranges from +1‰ to –23‰ with an average of -12‰, reflecting the effects of evaporative enrichment as shown by Cl.

The MG profile consists of pure sand, with noticeable changes in colour and texture at different depths (Fig. 3). The generally sandy MG profile shows moisture content over a narrow range, and mostly less than 5%. This profile has low solute concentrations, with chloride ranging from 5 mg/L to 170 mg/L while nitrate ranges from 1 mg/L to 150 mg/L (Table 3). Deuterium is expressed as δ-values, the deviations in parts per mille from the International Standard V-SMOW; this ranges from –14‰ to –39‰ with an average of -26‰.

The equation $R_d = C_pP/C_s$ is used to calculate direct recharge R_d [6] where C_p is the mean chloride in rainfall, P is the long term mean average annual rainfall amount and C_s mean chloride concentration in the unsaturated zone. Values used are C_p (1.7 mg/L) and mean annual rainfall (P) of 389 mm. The mean unsaturated zone Cl concentration C_s for the MF profile from the upper 3m is 47 mg/L and from the lower section (3-16 m) is 2892 mg/L. From these input data estimated the direct vertical recharge for the top 3m at the MF site is 14 mm/a and 0.2 mm/a for the lower section respectively. This confirms that active recharge is only taking place to 3 m and that below this little or no water is passing through the lower section at the present day.

In the case of the MG profile C_s is 29.5 mg/L and, using the same average rainfall amount and chloride in rainfall, the estimated rate of recharge is 22.5 mm/a, while the residence time of water over the depth sampled is 21.4 years. Table 3 summarises the recharge estimates for the profiles in the present work as well as from other profiles in the area obtained under a BGS and Oxford University initiative (the Sahel project) funded by NERC UK [8].

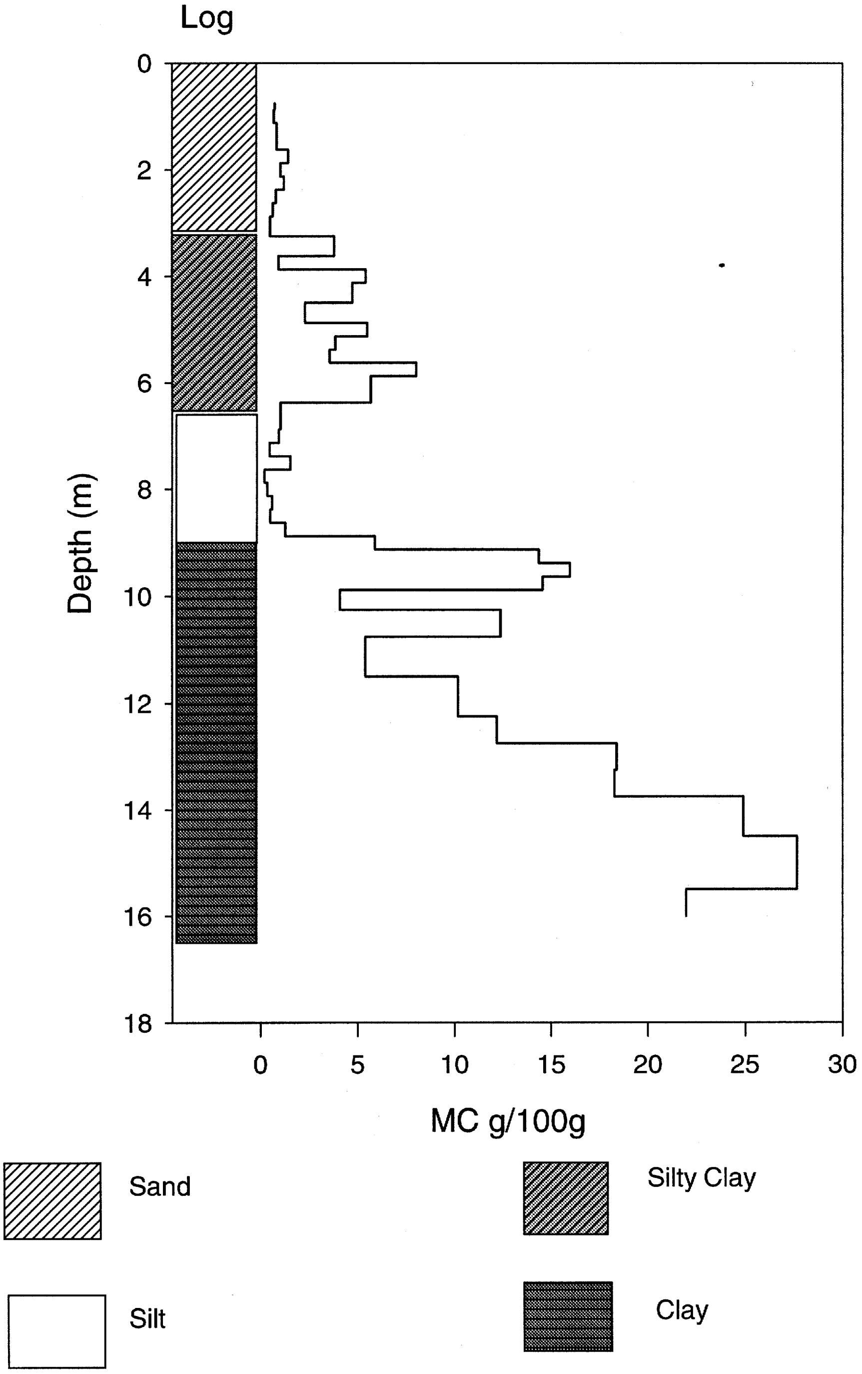

Fig. 2. Depth distribution of lithology and moisture content for MF profile.

Water analyses from river and groundwater show that the concentrations of major ions are generally low. Chloride and nitrate concentrations areless than 5 mg/L and 0.5 mg/L respectively (Table 4).

Table 1. Rainfall amount and chloride concentration

Year	Station	Rainfall (mm)	Weighted Cl (mg/L)
1992	Kaska	320.5	2.83
1993	Kaska	327.3	1.28
1992	Alkali	549.4	1.55
1995	Alkali	614.5	3.36
1996	Alkali	297.5	0.57
1997	Alkali	226.7	0.72
Average		389.3	1.72

4. Discussion

The topography of the study area is generally very flat with difference in elevation of <5 m over tens of kilometers [9], however, the dune ridges and interdunal depressions are local exceptions. The numerous depressions or playas in NE Nigeria at almost the same elevation of ~300 m and characteristic clay deposits imply a surface related to former lake extension (Lake Mega Chad). The clay deposits probably representing the floor of this former mega Chad underlie the dune ridges in some places. At present the average level of Lake Chad is at ~282 m, which is higher than the water table at 275 m [10] and the lake at the present day (if present) probably acts as a recharge source. Thus the groundwater flow direction is to the southwest, away from the Lake [9].

The 3 upper metres of the MF profile contains low concentration of chloride and other conservative solutes - bromide and nitrate (Fig. 4). This indicates present day atmospheric origin for these solutes, which are progressively washed into the profile during the subsequent rainy seasons and accounts for the lack of accumulation of salts in the surface. The concentrations of chloride in the upper 3m indicate a recharge rate of 14 mm/a (similar to MG profile with 22 mm/a); the difference is attributable to relatively finer sediments of the upper 3 m of the MF profile.

The concentration of chloride for the lower part of the MF profile (Fig. 4) is quite distinct and brackish with one peak at a depth of 9 m with chloride concentration of up to 7000 mg/L. The lower impermeable lacustrine deposits (mainly clays) below 3 m probably represent the former bed of Lake Chad where little or no infiltration has been occurring since the lake extended over this area during the mid Holocene. Schneider [11], has mentioned the existence of large palaeolake Chad at the 320 m level at about 6000 yr B.P. During this period it must have invaded large areas including the area of the MF site and deposited beds that are of low permeability. The lower profile therefore consists of waters of low mobility, a partial relic of the former lake sediment pore waters.

Bromide (and Br/Cl) has been used as an additional tool to investigate the origins of Cl and its use as an environmental tracer has been discussed elsewhere [12, 13]. The interstitial water samples from MF profile have been plotted in Fig. 4 and then in the Br/Cl plot (Fig. 5) where the two sets of data above and below 3m are separated. The hiatus in the source of Cl is clearly shown in the depth plot. Both these sets of data lie above the marine line (Br/Cl = 0.00353) indicating Br enrichment. The upper 3m has a mean ratio of 0.031 significantly higher than the lower, more saline profile (Br/Cl of 0.0117). Local Br concentrations in rainfall from the two stations [6] also show enrichment over Cl when compared to the marine ratio, where all data points fall above the marine line with a mean Br/Cl ratio of 0.007. The enrichment of Br relative to Cl has been observed in soils as well as the in unsaturated zone [14] and is likely to be related to the breakdown of organic matter, which is selectively enriched in Br. The data imply that the source of strong Br/Cl enrichment is initially from rainfall, but that subsequent enrichment takes place in soil horizons and/or lake deposits.

Table 2. Solutes and deuterium concentrations in MF profile

MF Profile elutriation				
Depth (m)	corr Cl (mg/L)	corr Br (mg/L)	corr NO_3-N (mg/L)	δ^2H
0.75	57	1.95	16	-22
1.00				
1.25	35	1.65	14	-30
1.50	35	1.58	14	-37
1.75	12	0.68	8	-29
2.00	29	0.41	12	-27
2.25	24	0.40	10	-32
2.50	37	0.30	15	-39
2.75	64	2.22	19	-27
3.00	173	5.20	116	-28
Average	**47**		**22**	**-30**
3.50				-21
3.75	795	9.04	789	-4
4.00				-7
4.25	1670	21.07	1400	1
4.75	1228	14.38	941	-8
5.00	1273	15.01	1064	-12
5.25	3320	22.72	1573	-12
5.50	2454	27.89	1543	-6
5.75	2560	37.89	861	-2
6.00				-9
6.75	4114	51.13	423	-9
7.00	1518	18.20	176	-6
7.25	5185	65.38	726	-5
7.50	2437	29.71	373	-22
7.75	6944	80.91	1122	-20
8.00	6624	78.25	1118	-23
8.25	5328	65.42	927	-12
8.50	5365	64.49	920	-9
8.75	2796	34.19	528	-12
9.00	2834	35.95	567	-1
9.25	4738	61.36	943	-15
9.50	5861	77.51	1221	-20
9.75	6192	77.54	1254	-16
10.00				-16
10.50	3742	45.25	1170	-17
11.00	2442	28.97	993	-13
12.00				-21
12.50	2832	35.26	1432	-20
13.00				
13.50	1627	23.60	745	-15
14.00				-18
15.00				-16
16.00				-13
Average	**2892**		**786**	**-12**

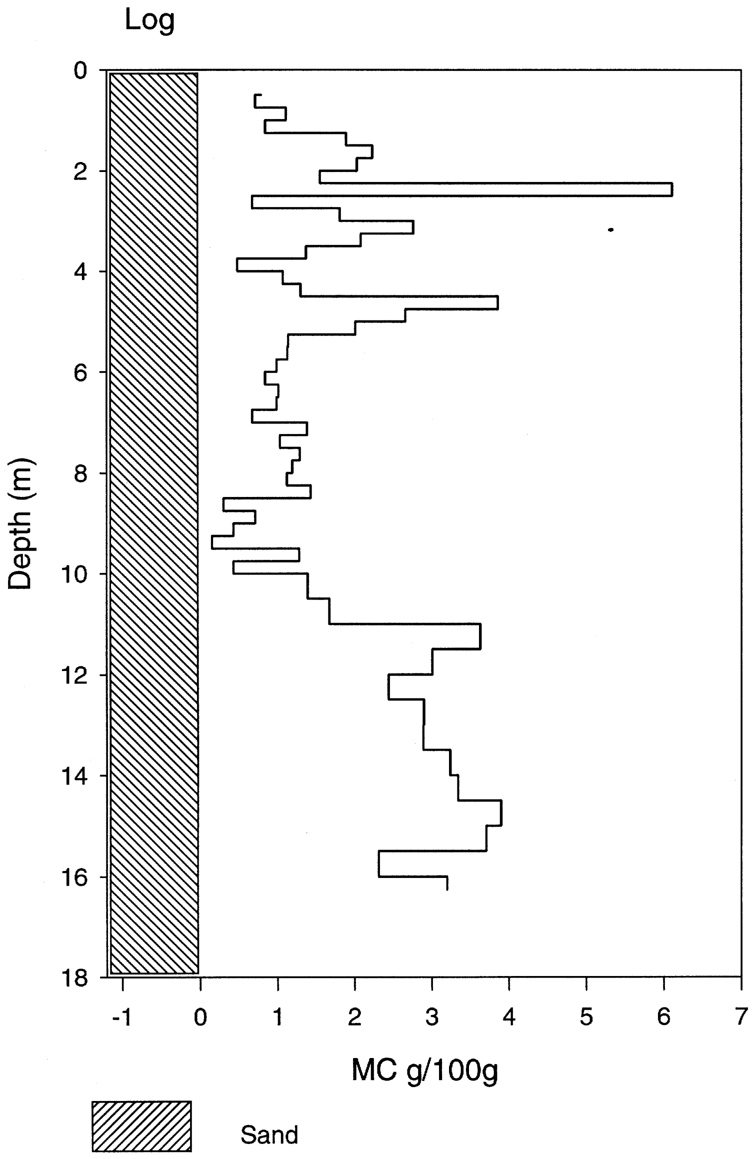

Fig. 3. Depth distribution of lithology and moisture content for MG profile.

The MG profile has relatively low concentrations of Cl and NO_3-N. The mean chloride concentration is 29.5 mg l^{-1}, and its relative uniformity down the profile (Fig. 6) demonstrates that homogenous displacement of an atmospheric input value is the main control. Oscillations about the mean may, however, relate to *recent* antecedent climatic variations. Recharge estimated from the chloride technique gives a long term average of 22 mm/a spanning the period of ca 21 years. Rates of recharge could have been higher in the past, especially since the last 21 years represent the period of Sahel drought.

There is a reasonably good agreement in the estimated rate of recharge between the upper 3 m of the MF profile, the MG and the earlier profiles in the Manga Grasslands [8,14]. Both sites in the present study (upper MF and MG profiles) give therefore recharge estimates of 14 to 22 mm a^{-1}, although at the MF profile an impermeable clay layer encountered below 3 m depth has limited the vertical percolation of moisture. Estimates of recharge for the Manga

Table 3. Solutes and deuterium concentrations in MG profile

MG Profile elutriation			
Depth (m)	CorrCl (mg/L)	corrNO$_3$-N (mg/L)	δ^2H
0.50	31	47	-14
0.75	42	35	-36
1.00	15	45	-37
1.25	16	41	-31
1.50	64	55	-24
1.75	11	18	-30
2.00	9	9	-28
2.25	17	13	-21
2.50	4	4	-14
2.75	27	49	-27
3.00	9	8	-39
3.25	6	4	-30
3.50	9	7	-20
3.75	16	11	-23
4.00	50	110	-25
4.25	28	39	-28
4.50	19	23	-23
4.75	9	12	-26
5.00	17	18	-27
5.25	26	53	-18
5.50	54	152	-19
5.75	54	164	-26
6.00	49	95	-26
6.25	52	93	-28
6.50	44	78	-32
6.75	35	40	-21
7.00	35	9	-26
7.25	22	4	-30
7.50	37	12	-28
7.75	27	14	-28
8.00	30	31	-21
8.25	26	60	-11
8.50	17	26	-29
8.75	78	100	-26
9.00	39	51	-23
9.25	95	84	-23
9.50	172	160	-22
9.75	23	10	-23
10.00	64	14	-25
10.50	15	4	-29
11.00	9	7	-33
11.50	17	4	-33
12.00	8	2	-27
12.50	10	3	-25
13.00	6	5	-19
13.50	10	4	-34
14.00	8	4	-31
14.50	9	4	-29
15.00	10	7	-31
15.50	9	5	-18
16.00	30	16	-21
16.26	17	28	-34
Average	**29**	**36**	

Table 4. Unsaturated zone profiles and recharge estimates from N.E. Nigeria. The MF and MG sites are from the present study with other data from Edmunds et al. (1999)

Profile	Depth (m)	No. Samples (n)	Mean Cl Cs (mg/l)	Mean annual recharge Rd (mm/a)	Residence time (years)
GM 1	15.50	51	14.1	44.0	17.6
KA 1	14.75	50	18.3	33.9	13.8
MD 1	22.50	65	11.5	53.9	14.3
MN 1	16.50	53	41.6	14.9	34.0
N-TM	18.75	58	11.7	53.0	16.2
MG	16.26	53	29.46	22.5	21.4
MF (upper)	03.00	10	47	14	09
MF (Lower)	16.00	42	2892	0.2	16677

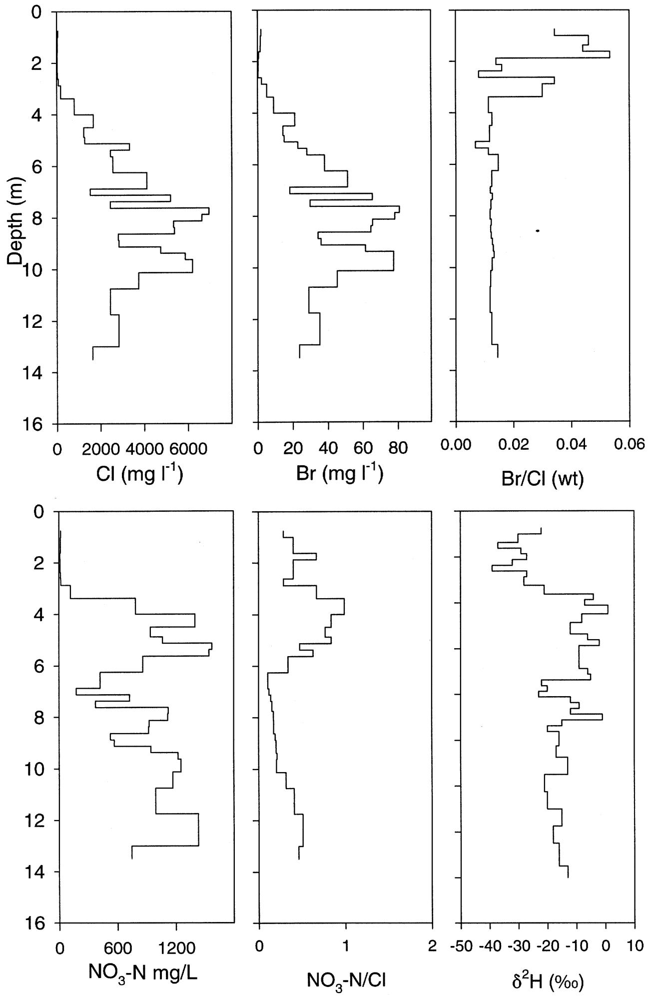

Fig 4. Cl, Br/Cl, NO$_3$, NO$_3$-N/Cl and δ^2H values in interstitial waters from the unsaturated zone for the MF profile.

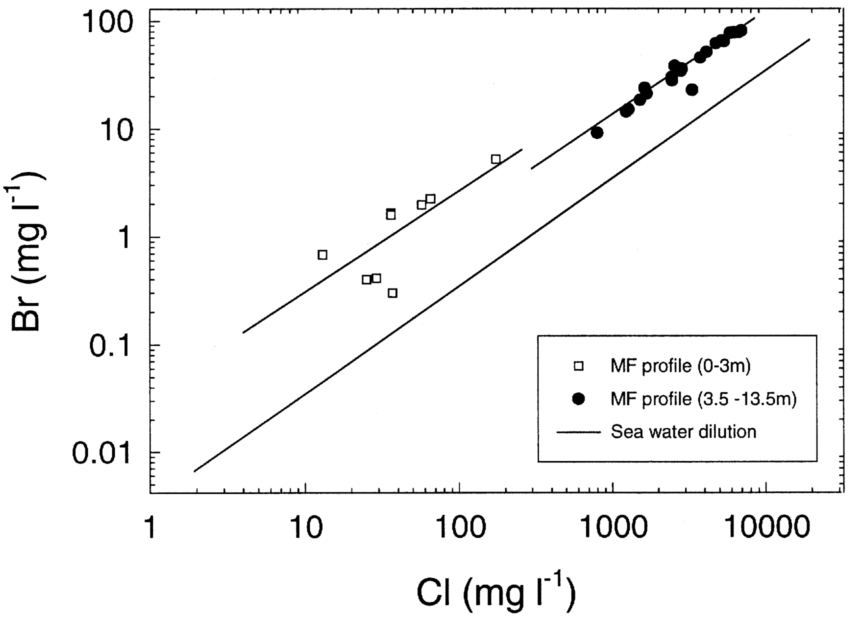

Fig. 5

Grasslands sites give a range of 14 mm a^{-1} to 53 mm a^{-1} (Table 4). Edmunds et al. [14] have used regional groundwater chloride to obtained an average long term recharge estimate of 60 mm a^{-1} for NE Nigeria. High recharge rates therefore occur over much of the sand-covered area of the Sahel of NE Nigeria. These high estimates must imply either that at the regional scale other sources of recharge, probably ponding and surface runoff, may also contribute significantly in addition to direct recharge via the unsaturated zone, or that estimates from the MG and upper MF profiles only indicate low recharge rates during the period of the prolonged drought from the early 1970's.

Water samples from local wells have been used to provide a check to the estimation of recharge using the unsaturated zone chloride profile technique. Chloride concentrations in the water table from Barikuraram well, situated about 100 m from the MF profile, give a relatively high concentration of 189 mg/L (Table 4) when compared to the 47 mg/L average chloride concentration for the upper MF profile. This indicates that solutes from the evaporated lake sediments are also likely to have been incorporated.

The major ions of two of the wells (Lambawa and Abadam) closer to river Yobe show concentrations that are similar but slightly enriched relative to the river. Chloride for instance show slight increase in concentration from 1.6 mg/L in the river water to 2.2 and 3.6 mg/L in the wells (Table 4), which is attributable to evapotranspiration. Similarities in the major ion concentrations indicate some hydraulic links between the river and groundwater systems. This further adds weight to the possibility of recharge taking place laterally from the river Yobe, which is at higher elevation in relation to the groundwater level to the wells close to the river channel.

Depth concentrations of NO_3-N and chloride in the MG profile (Fig. 6) show similar peaks and troughs (although different amplitudes), supporting the conservative behaviour of nitrate. In the upper 3m of the MF profile total nitrate concentrations are enriched (average 22 mg l^{-1} NO_3-N) with some concentrations approaching NO_3-N/Cl ratios of 0.5. Below 3 m very high nitrate concentrations are found with an average of 786 mg/L NO_3-N. There is a clear separation at about 6m between a zone with very high NO_3-N ratio and a lower zone less enriched in nitrate; this division corresponds to the geological log and must be related to conditions of deposition. Once nitrate has entered the largely inorganic and aerobic unsaturated zone, it will behave as a conservative anion and its geochemical behaviour will be similar to chloride. Denitrification is likely to be insignificant under oxidising conditions of most semi-arid environments, especially where water contents are low and organic C contents are also low. As well as the high nitrate concentrations the very low Fe concentrations

Table 5. River and groundwater chemical data

Locality	**Point Type**	**Temp**	**Ph_Lab**	**Sec**	**$\delta^{18}O$**	**δ^2H**	**Na**	**K**	**Ca**	**Mg**	**Hco3_Lab**	**So4**	**Cl**	**No3_N**
River Yobe	river	28.6	7.62	108.3			8.4	4.6	7.48	2.39	59.6	2.3	1.6	-0.5
Barikuraram	well	30.3	8.27	4170	-2.4	-30	864	26.1	60.3	75.9	1765	374	189	64
Lambawa	well	33	7.64	259	-1.1	-14	15.5	6.5	21.8	6.31	134	9.8	3.6	0.52
Abadam	well	33.8	7.79	31.8	-0.6	-7	33.7	8.5	24.2	5.94	212	0.3	2.2	-0.5
Alagarno	well	30.1	8.05	1738	3.4	16	274	37.6	90.8	45.3	785	238	42.1	1.14
Abadam	BH	31.8	7.84	907	-7	-43	145	15.7	27.5	12.2	192	202	60	0.98
MF Doro	BH FF	41.3	7.98	1021	-6	-47	150	16.1	33.8	14.1	204	244	63.5	-0.5
Duhuri	BH FF	36.3	7.93	10510	-5.7	-46	148	16	31.6	13.5	195	226	65.1	1.14
Arege	BH FF	38.8	8.11	998	-6.8	-51	158	16.2	34.4	14.5	209	240	62.1	-0.5
Bundur	BH FF	41.5	7.93	595	-6	-48	101	7.8	7.68	3.35	191	71.3	23.8	1.92
Kekeno	BH FF	39.3	8.08	470	-6.8	-50	84.1	7.1	6.08	2.76	209	38	17	-0.5

Well = Dug well BH = Borehole BH FF = Borehole Free Flowing

(generally below detection limits) are also indicative of oxidising conditions. Total NO_3-N concentrations derived from atmospheric inputs in the Sahel are low [6, 16]. Subsequent variations in the concentrations of nitrate will be modified by physical processes (evapotranspiration) or biochemical transformations in the soil and rooting zone [17].

The nitrate concentrations in MG profile show quite wide variations but with some similarity to the Cl profile. Concentration maxima (at 6 and 9m) are however found at two intervals which are also seen in the NO_3-N/Cl profile where strong enrichment (up to 3.5 times Cl) reflects nitrate being the dominant anion in the profile. This must reflect changes in input conditions (land use/vegetation) over the past 20–30 years, but an explanation is not readily available.

The result of stable isotope analysis for 1997 rainfall at Garin Alkali meteorological station shows a linear regression line through the data points and is similar to the meteoric water line, but the relationship is: $\delta^2H = 6.33\delta^{18}O + 9.9$ with a correlation coefficient of $r = 0.92$. The range for $\delta^{18}O$ is from –6.8‰ to +4.2‰, and for δ^2H is from -36‰ to +36‰. These values are slightly enriched and indicate modification due to evaporation in the monsoon rains producing departure from the GWML. Detailed discussion on the isotope chemistry of rainwater of the region is given in [6].

Depth distribution of δ^2H for the profiles is shown in Figures 4 and 6. The deuterium profiles broadly reflect the trends shown by chloride, especially in distinguishing the active, present day recharge section from the evaporated section in the MF profile. The mean value of δ^2H in profile MG is –26‰ which is slightly more enriched than but similar to the upper

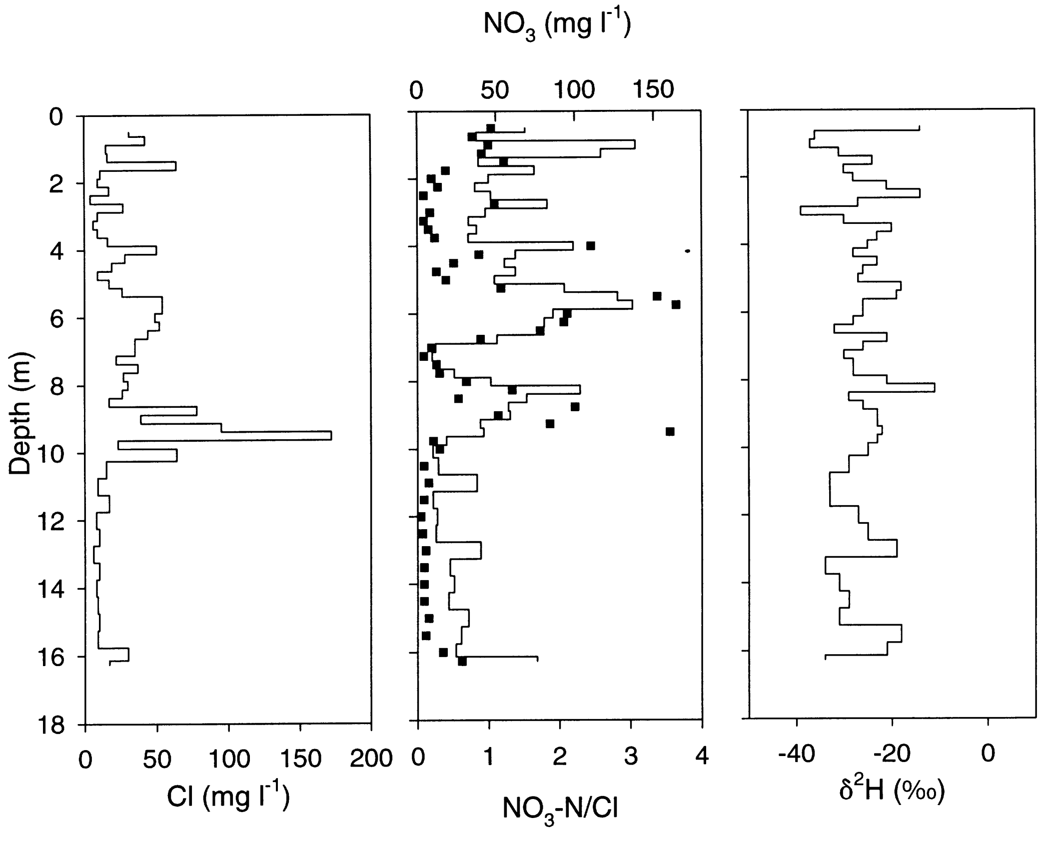

Fig. 6. Solute concentrations and deuterium in the MG profile. On the NO_3-N/Cl diagram NO_3-N concentration is plotted as solid symbol.

section of MF (-30‰). This compares with the mean δ^2H of –10.4‰ in local rains. It is possible that the discrepancy relates to the non-representativeness of the rainfall inputs for this area, since it would be expected that the unsaturated zone samples would be enriched due to evaporation as compared with rainfall.

In the MF profile (Fig. 4) depth distribution of deuterium clearly separates the upper 3 m with an average δ^2H of -30‰ from the lower section with an average δ^2H of -12‰. The fact that the lower section of MF profile has relatively enriched deuterium and also high concentration of solutes shows that relative evaporative enrichment is the likely control, in line with the Cl results. Small oscillations of deuterium values in the lower MF profile may indicates cycles of flooding of Lake Chad during former climatic conditions.

The result of stable isotope analysis for 1997 rainfall at Garin Alkali meteorological station, MF unsaturated zone moisture (the lower section) and groundwater from shallow dug wells were used to plot a delta diagram (Fig. 7). The unsaturated zone moisture and groundwater from some of the wells plot in the same area and have δ^2H value ranging from -14‰ to +2‰ and δ^{18}O from –1.3‰ to +1‰. These wells are few metres away from river Yobe, and get recharged with heavier water from an evaporated river Yobe, thus plotting in the same area as the evaporated lower section of MF. Solute concentrations also show that there is

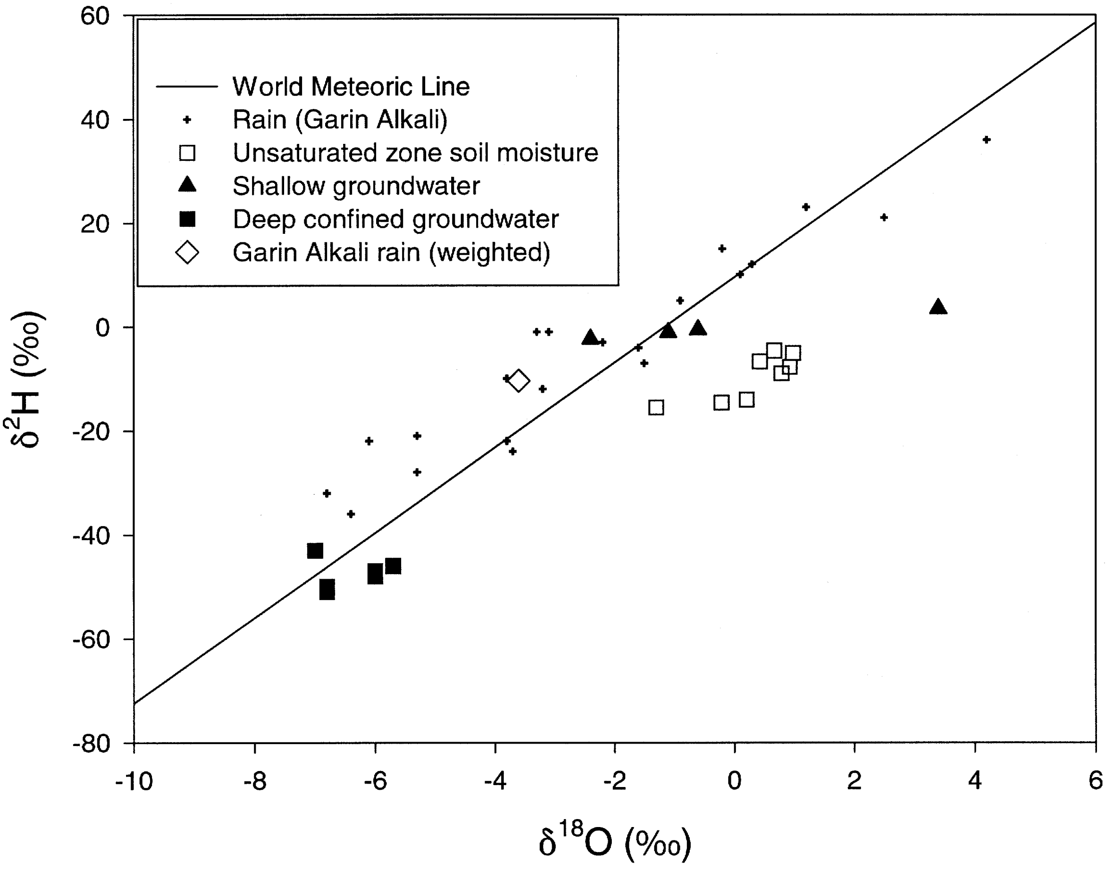

Fig. 7. Plot of 18O versus d2H for rainfall, unsaturated zone moisture, shallow groundwater and deep confined groundwater.

hydraulic link between the river Yobe and the wells close to it. Groundwater from Barikuraram the closest well to the MF profile shows a depleted stable isotope with $\delta^2H = -30‰$ and $\delta^{18}O = -2.4‰$. Barikuraram well is ~2 Km from river Yobe, and might be receiving its recharge mainly from heavy rains that are depleted in stable isotopes. This also shows that recharge from river Yobe is restricted to wells within only a short distance (tens of metres) of the river channel.

5. Summary and conclusion

Manual augering was used to obtain interstitial waters from two profiles in the unsaturated zone of NE Nigeria to depths of 16 m. This technique is robust and effective in sandy and silty soils. Drilling through clay-rich sediments was also achieved, although thick plastic clays were not able to be sampled. Results of hydrochemical data (solutes and stable isotope) from rainwater, unsaturated zone soil moisture and groundwater from the phreatic aquifer were used to estimate the amount of recharge via the sandy unsaturated zone to the semi-arid region of NE Nigeria. The chloride profile technique gives an estimated direct vertical recharge rate of 14 mm/a and 22.5 mm/a, and residence times of 9 years and 21 years for the upper 3m MF and MG profiles respectively. Below 3 m depth in the MF profile there is a low permeability silt/clay sequence which probably represents the bed of the former lake Chad. The concentration of solutes coincident with enriched deuterium values in the interstitial waters of this section point to an evaporative enrichment and a recharge regime unrelated to the present day. Br and NO_3-N have been used to interpret the source of the solutes, and together with deuterium give the trend of the recharge processes and an insight into the past climate and environments.

In the sand-covered areas of the Sahel of NE Nigeria therefore significant direct vertical recharge takes place via the unsaturated zone, which on a regional scale is complimented by surface runoff. The amount of recharge can sustain the present local abstraction via dug wells, however caution has to be exercise in using submersible pumps to exploit this resource.

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Environmental isotope profiles of the soil water in loess unsaturated zone in semi-arid areas of china

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Abstract. According to the IAEA Research Contract No. 9402, soil cores CHN/97 and CHN/98 were taken from loess deposits of China in Inner-Mongolia and Shanxi Province, respectively. Isotope and chemical constituents of the interstitial water from these cores, compared with data obtained from the same places before, were used for estimating the infiltration rate. Tritium profiles from the loess unsaturated zone show clearly defined peaks of 1963 fallout. It implies that piston-flow model is the dominant process for soil water movement in the highly homogeneous loess deposits. It has been shown from this study that vertical infiltration through the unsaturated zone accounts for 12% - 13% of the annual precipitation and perhaps is not the main mechanism of groundwater recharge in semi-arid loess areas.

1. Introduction

For assessment of the ground water resources on the basis of the water balance, the most important parameters are the recharge and discharge rates, which are difficult or impossible to determine by conventional methods. The isotopic composition and chemical constituents of water infiltrating through the unsaturated zone into groundwater aquifer can be employed to determine these parameters. Several studies have shown that stable isotope profiles in soil water in arid and semi-arid areas can be interpreted in terms of evaporation rate [1,2]. While in humid areas these profiles may be used for estimating the infiltration rate [3]. The radioactive isotope tritium, which was released to the atmosphere and hydrosphere by bomb tests during the late fifties and early sixties, is of particular use for recharge rate determination [4]. The maximum of its concentration in soil water profiles may represent a time marker, if the soil is homogeneous and the infiltration rate is low enough and the tritium peak of 1963 is still in the unsaturated zone.

In 1988 through 1990, in corporation with the Paris-Sud University, France, we were involved in study of recharge and discharge processes in semi-arid area of loess cover in Inner-Mongolia by means of environmental isotopes. The core CHN/88 of about 20 meters in depth was taken in loess deposits in 1988. A clear tritium peak of the soil water from this core shows that loess is very special, and it is most suitable for this kind of research. According to the work plan of the Agency Research Contract No. 9402, an additional core was taken in the same place of coring in 1988 in Inner-Mongolia. Besides, another core was taken from the loess deposits in Shanxi province. In this final report, all the results obtained will be summarized.

2. The characteristics of loess

Loess is a very special, yellow in color, Quaternary deposit. It is porous, silty and earthy, and is unstratified and calcareous, and is believed to have an aeolian origin.

Predominance of silt-sized particles and enrichment of carbonates commonly characterize the composition of loess. Quartz grains compose over half of the silt-sized particles. Loess in China, developed on various geomorphologic units, shows approximately the same grain-size distribution. The major fraction of loess is 0.05-0.01 mm, which accounts for about 45-60%; the next is < 0.005 mm fraction, accounting for about 15-25%. The variation in the content of these two fractions provides an informative clue to understanding the sedimentary cycle and climatic fluctuation. There are almost no grains greater than 0.25 mm. This fact favors the origin of loess as an aeolin deposit.

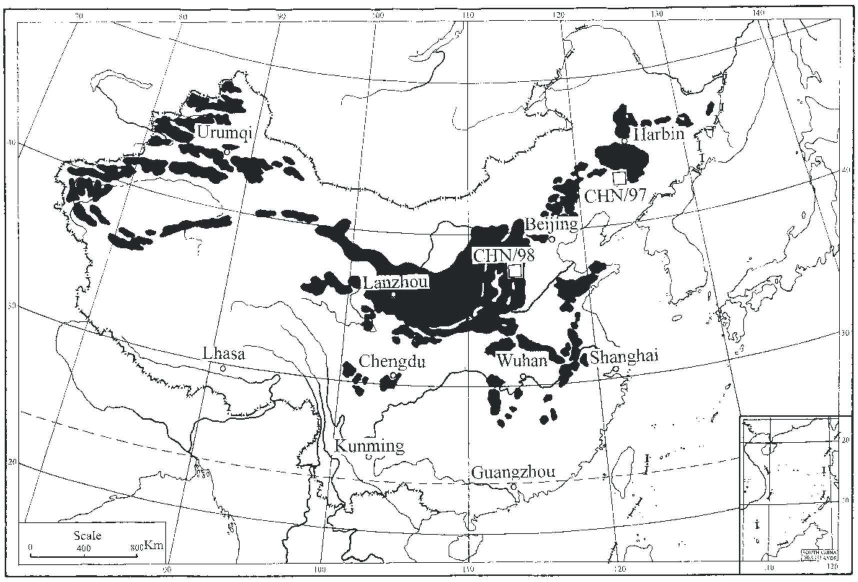

Fig. 1. Sketch map showing the loess distribution in China (after Liu Tungsheng et al. [5]) and sampling sites of the cores CHN/97 and CHN/98.

Loess has specific mechanical or construction property. Loess logged with water often shows significant collapsing, rapid subsidence and lateral rheologic behavior. Collapsing loess usually has dry bulk density (γ d) less than 1.28 g/cm^3. Loess with γ d more than 1.40 g/cm^3 shows no collapsing.

Loess covers about 10% of the land surface of the Earth and is concentrated in the temperate zones and in semi-arid desert margins. In China, loess is widespread in its northern and northwestern part and occupied about 440,000 km^2. The best-developed loess lies between 34°and 45°N, along the middle reaches of the Yellow River, in the so-called Loess plateau (Fig. 1), where it attains its greatest thickness (100 – 200 m).

Loess covers the Tertiary, or other old strata, forming different kinds of loess landforms, in which unconfined aquifers are developed. On the top of the basement quite often there is a layer of impermeable clay. Loess is known as highly homogeneous and porous, and may be regarded as permeable, but these unconfined aquifers can produce only small quantities of water. These aquifers are recharged not only by infiltration of interstitial water downwards from the land surface, but also by the surface flow through deep valleys, or through vertical cleavages, which may not be found in other unconsolidated rocks, but are generally developed in loess deposit.

3. Geography and climate conditions of the sampling sites

The core CHN/97 (118°56'E, 42°52'N) is located in Wudan county, Inner-Mongolia Autonomous Region (Fig.1). Main reasons for this choice were: (I) homogeneity and wide geographical extension of the deposit which allow the results to be extrapolated; (ii) semi-arid climatic conditions marked by a low rainfall of about 360 mm/year, where agricultural and cattle development is entirely depending on ground water and soil water; and (iii) a core has already been taken in 1988, it will be very interesting to compare the isotopic profiles from the cores in the same place after a time interval of 9 years.

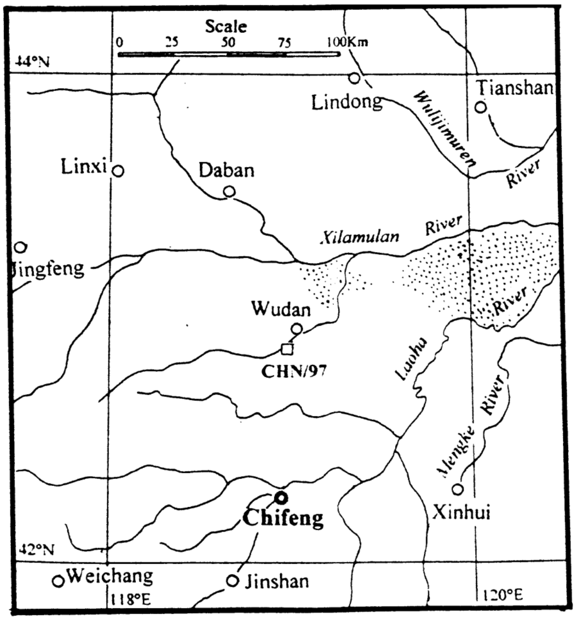

Fig. 2. Sketch map of the sampling site CHN/97.

Sampling site is at 12 km south to the Wudan City (Fig. 2). Distance between the core CHN/97 and the core CHN/88 is about 40 meters. The site for coring is free of vegetation. It is no surface run-off during the rainy season and never is irrigated. The sampling site is relatively flat and far from the river valleys. Therefore, the vertical movement of the soil water should be dominant.

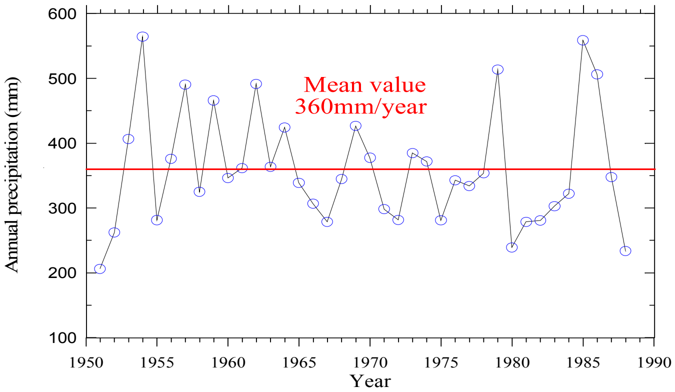

Fig.3. Annual precipitation in Wudan county. (Data from the Wudan Meteorological Station).

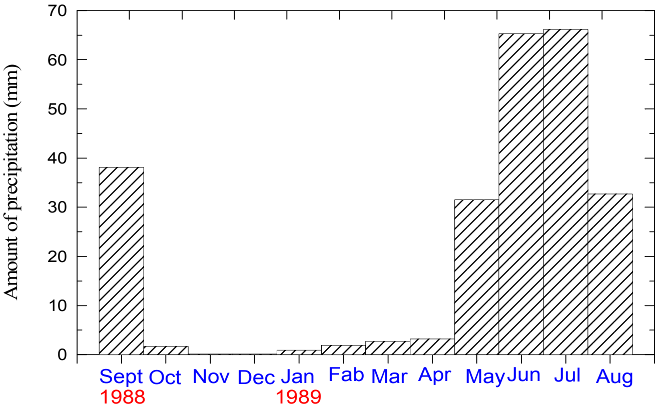

Fig. 4 Distribution of rainfall in Wudan county. (Data from the Wudan Meteorological Station).

The climate in Wudan County is characterized by relatively low rainfall. Annual precipitation is 360 mm/year (Fig.3), which is distributed mainly in May through September (Fig.4). Water in rivers is only in the rainy season. This is typical for the northern and northwestern parts of China. A thick loess cover is widely distributed in this region. Desert with moving dunes is developed in limited area in the north and northeast to the Wudan County (Fig. 2), showing the serious semi-arid conditions.

The core CHN/98 was taken in May, 1998, in Zhangzhuang village, Pingding county, Shanxi province (113°41'E, 37°41'N) (Fig.1), where loess deposits have wide and homogeneity geographical extension.

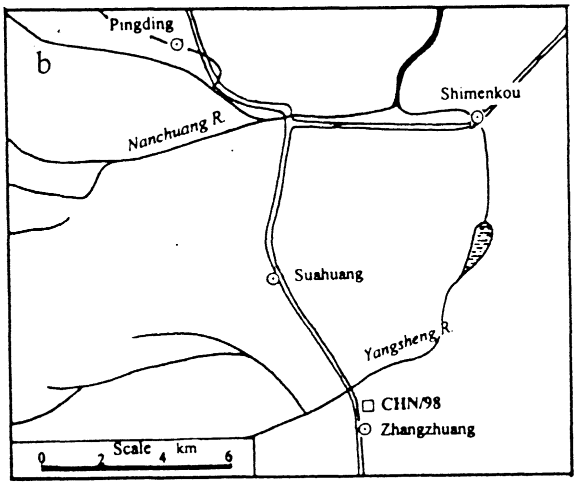

Fig.5. Sketch map of the sampling site CHN/98.

Sampling site of core CHN/98 is 400 meters north to the Zhangzhuang village, located on the watershed between two small rivers (Fig.5). In 1985, a test pit was made by Zhang Zhigan et al. in this sampling site for estimating the tritium content in soil samples [6]. Distance between the test pit of 1985 and the core CHN/98 is about 50 meters. The site for coring is relatively flat and it was never irrigated. There is no surface run-off during the rainy season. Therefore, the vertical movement of the soil water should be dominant.

Shanxi province is in the northern limit of the monsoon climate. The climate conditions are semi-arid with relatively low rainfall. Mean annual precipitation is about 550mm/year. Variations in summer monsoon strength lead to greater changes in amount of precipitation. For instance, annual rainfall in 1997 was 696 mm, but it was only 269 mm in 1996. There is water in rivers only in rainy season, because rainfall is mainly concentrated in May through September. This is typical for small rivers in loess plateau. Fig.6 illustrates the climatic conditions in the area under investigation. The Yangquan City is located about 30 km to the north of the sampling site.

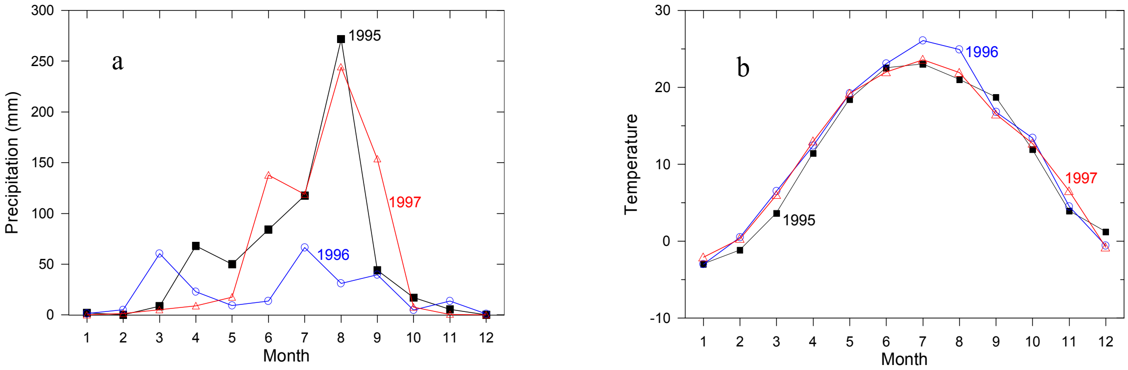

Fig.6. Monthly precipitation (a) and mean ground temperature (b) in Yangquan city. (Data from the Yangquan Meteorological Station).

Loess cover divided by river systems is widely distributed in this region. Thickness of the loess deposits is tens to hundreds meters. Underlying base rock is Carboniferous containing coal seams, which are exploited by small open pit mines. On the top of the basement there is a layer of impermeable clay. Therefore, loess deposits can be considered as an unconfined aquifer, although our cores have not reached the water table.

4. Coring process

Soil samples were collected using a hand auger in intervals of 10 cm and 20 cm depth. A wood tower was built specially to make the coring easier. When bringing the soil sample to the ground surface, its temperature was measured and an aliquot sealed immediately in aluminum can with tape.

In the case of core CHN/98, when it reached the depth of 13.15 m, the hand auger could not move further because of a piece of gravel at the bottom of the core. A new core was about 4 m apart from the old one. Soil samples were taken after 13.15 m depth in intervals of 20 cm or 30 cm.

The maximum depth of the core CHN/97 was 1515 cm. All together 92 soil samples were taken from this core. A groundwater sample was collected from the well in the village Shanzuizi, which is located 3 km to the west of the core CHN/97. A snow water sample was collected on 7th of May, 1997, during a heavy fall of snow.

The maximum depth of the core CHN/98 was 1550 cm. All together 82 soil samples were taken from CHN/98 core. A groundwater sample was collected from the well in the village Zhangzhuang. A rain water sample was collected on 1st of May, 1998, during a rain process.

5. Extraction of the soil water and laboratory analyses

Soil water was extracted from an aliquot of the soil sample by vacuum distillation at 70°C and trapping the vapor in liquid nitrogen. Weigh soil sample of about 120 g , put it in a special designed glass bottle, and connect the bottle to the vacuum line. Freeze the soil sample with dry ice bath at first, then evacuate it. Heat the soil sample in a 70°C bath for 5 hours, at the same time collect the water vapor in a glass tube with a nitrogen trap. Then take off the nitrogen trap and wait for the ice in the tube turned into water. After that dry air was admitted into the vacuum line for taking off the water tube. Check the completion of the extraction procedure by comparing the weight of obtained water with the loss of weight of the soil sample. The water content is calculated and the obtained soil water is ready for isotopic measurements.

Lixiviate the dry soil (after extraction) with 200 ml distilled water for 4 hours. The chloride content of the water after lixiviation is measured using ion chromatography and by conventional titration.

Water samples of 6 ml were prepared for direct tritium counting using Aloka low-background scintillation spectrometer.

92 ampoules of 3 ml soil water from the core CHN/97 were sent to IAEA laboratory for both δ^2H and δ^{18}O measurements. 58 ampoules from the core CHN/98 were sent to State Key Laboratory of Loess Deposits in Xi'an for δ^{18}O measurement.

6. Chemical profiles

Fig.7 shows the distribution of the water content and the soil temperature along the depth of the core CHN/97. Water content of the soil is in the range from 8% to 12%, mean value is 10.4%. The high values of water content are at the depth of 3m, 9m and 13m below the ground surface. The soil temperature at the depth of more than 9 m, was 11°C, which perhaps represents the annual mean ground temperature at the sampling site.

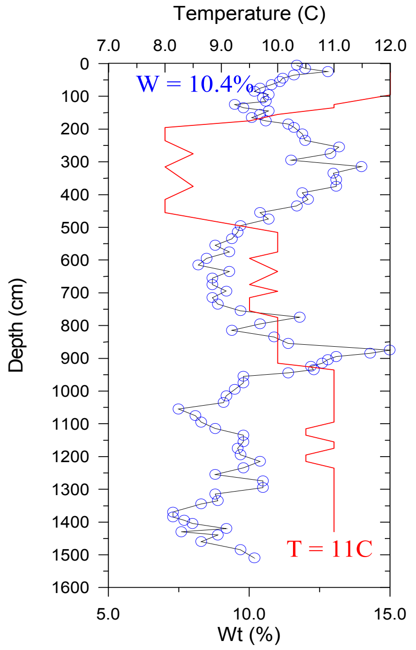

Fig. 7. Water content and the soil temperature along the core CHN/97.

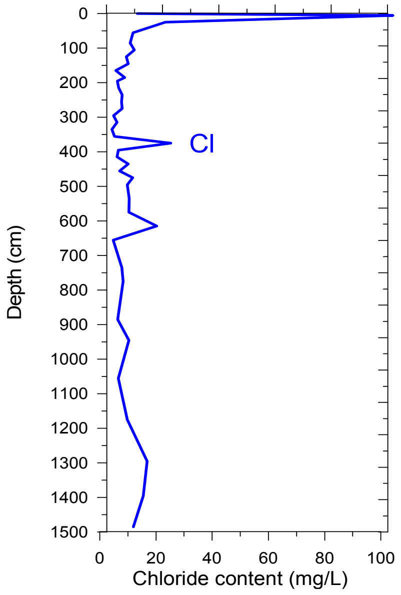

Fig. 8. Chloride content of the pore water along the core CHN/97.

Fig. 8 shows the distribution of the chloride content of the pore water. The maximum chloride content of 104 mg/L is at the depth of 10-20 cm. Several minor peaks are observed at the depth of 4 m, 6 m and 13 m. The chloride contents may be related to the evaporation peaks, and the $\delta^{18}O$ values of the soil water will show the same tendency. The mean value of the chloride content along the core below 1.5 m is 9.3 mg/L. It is the same as for the ground water sample from the well (9.05 mg/L).

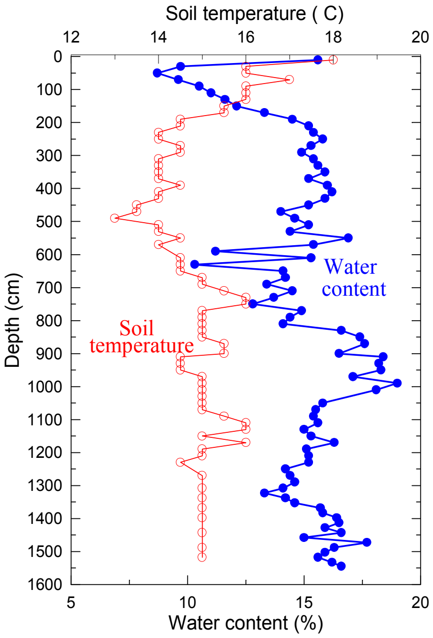

Fig. 9. Water content and the soil temperature along the core CHN/98.

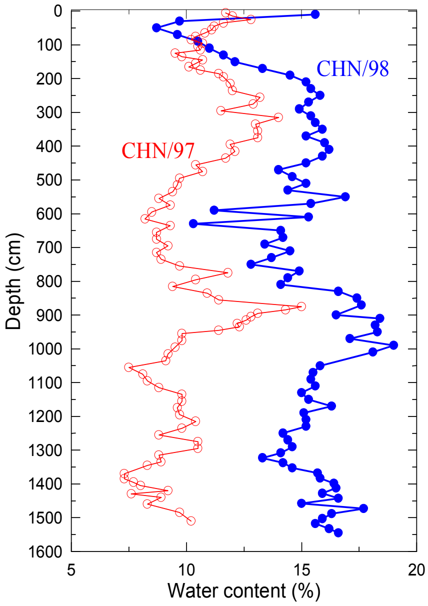

Fig. 10. Water content of the pore water along the core CHN/97 and CHN/98.

Fig.9 shows distribution of the water content and the soil temperature along the depth of the core CHN/98. Water content of the soil is in the range from 8.7% to 19%, mean value is 15%. The high values of water content are at the depth of 3m ~ 6m, 9.5m and 15m below the ground surface. The soil temperature at the depth of more than 7 m, was 15°C, which perhaps represents the annual mean ground temperature at the sampling site.

According to the piston flow model, the soil water infiltrates downwards because of the rain water recharge on the top of the unsaturated zone. Therefore, water content of the soil should be related to the amount of recharge, or annual precipitation. This is why distribution of the soil water alone the cores CHN/97 and CHN/98 has the same manner (Fig. 10). As samples from the core CHN/98 were taken one year later than those from the core CHN/97, the curve of which in Fig. 10 should be shifted about 30 cm downwards. It seems that two cores approximately have similar water content distribution. Higher water content was observed at the depth of 350 cm, 950 cm and 1480 cm. Low water content represents dry years, and high water content infers rather wet period, Curve CHN/97 in Fig. 10 is in the left from that of CHN/98 implies that annual precipitation in sampling site CHN/98 (550mm in Yangquan city) is higher than that in CHN/97 (360 mm in Wudan county).

Fig. 11 shows the distribution of the chloride content of the pore water and relative conductivity of the pore water along the core CHN/98. These two curves show similarity. The maximum chloride content of 78.9mg/L is at the depth of 2.7 m and it should be related to evaporation. There is another peak at the depth of 0.3 m, which represents a minor evaporation front of seasonal scale.

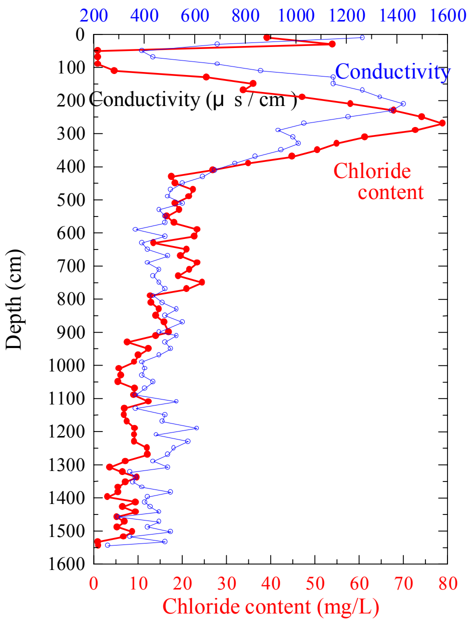

Fig. 11. Chloride content of the pore water along the core CHN/98.

7. Tritium profile of the core CHN/97

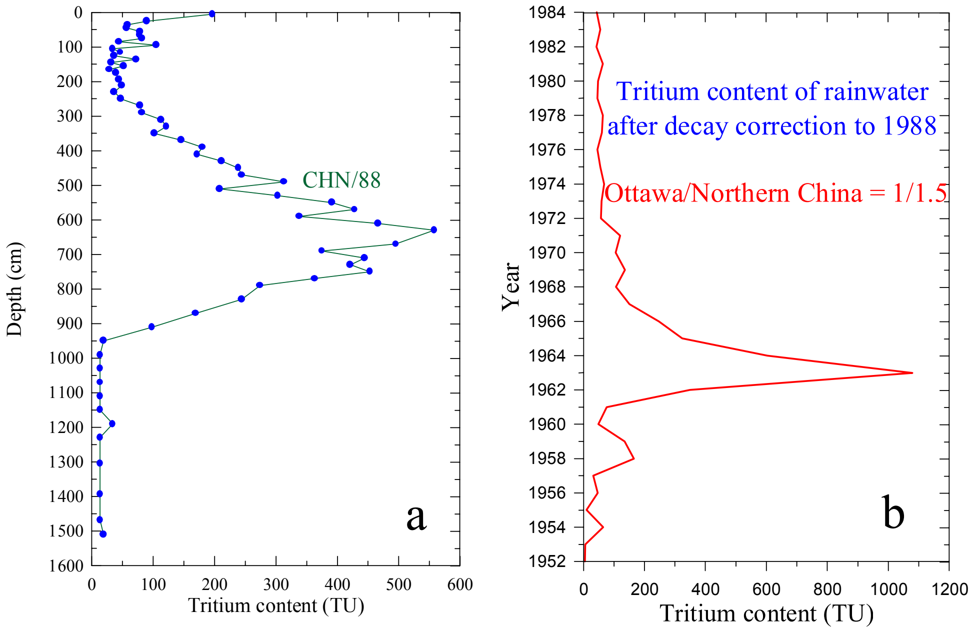

Fig.12 Tritium profile of the soil water from the core CHN/88 (a), and the distribution of the tritium content of rainwater in northern China [7] (b).

Fig.12 is the tritium profile of the soil water for the core CHN/88 which was taken by a joint team of three institutions (Institute of Geology and Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Paris-Sud University, France). The depth of the core was 20.75 meters. Tritium content of the soil water was measured in tritium laboratory of the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, in January and February of 1990. Values marked in this figure in Tritium Units were corrected to the time of sampling, August, 1988.

It can be seen from the Fig.12 a, that the tritium profile of the core CHN/88 shows a peak at the depth of 6.35 meters and a clear-cut rise above 10 meters. Tritium concentrations of the rainwater in northern China are given in Fig.12 b, which was reconstructed from calibration with the Ottawa long record [7]. The similarity is striking between the tritium distribution in the soil profile and in rainwater. This implies that piston-flow model is the dominant process for soil water movement in the highly homogeneous profile of loess deposits.

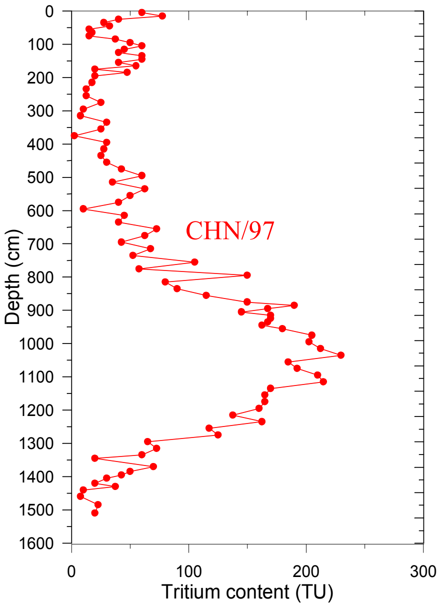

Fig. 13 Tritium profile of the soil water from the core CHN/97.

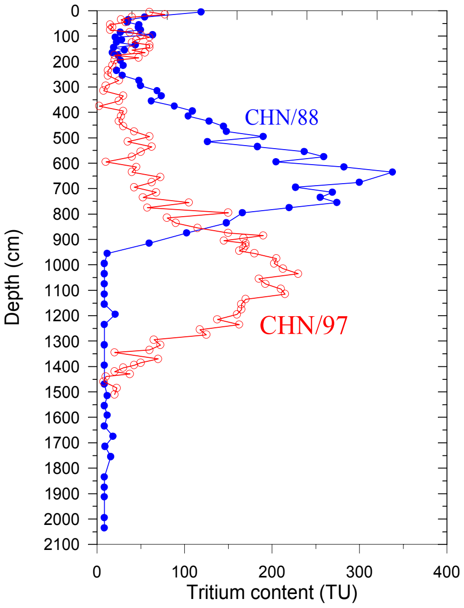

Fig.14 A comparison between the Tritium profiles of CHN/88 and CHN/97.

Fig.13 is the tritium profile of the soil water for the core CHN/97. A clear tritium peak is at the depth of 10.35 meters. The highest tritium content at the peak of core CHN/88 was 558 TU, whereas that in CHN/97 was 230 TU, less than the value 558 TU after decay correction (338 TU). These two tritium profiles are illustrated in the same scales (Fig.14), and the tritium values are presented for the year of 1997. As it can be seen from the Fig. 14, the bottom of the tritium peak triangle was 7.0 meters in 1988, whereas it is 8.5 meters in 1997. It implies, that the downward piston-flow is accompanied by dispersion.

The tritium peak moved downwards 25 cm per year according to the tritium profile from core CHN/88, but that from core CHN/97 gives a value of 30 cm per year. This difference implies, that the infiltration rate of the soil water downward is not a definite value, it may be dependent on several parameters, such as annual precipitation and so on.

Taking into account the water content of the soil 10.4%, the mean infiltration rate is 30 cm per year, and assuming an average wet density of 1500 kg/m^3, a mean recharge rate of 47 mm/a is calculated for the core CHN/97 during the past 34 years.

The water table of the shallow aquifer in the sampling site of core CHN/97 is at the depth of about 30 m. From the tritium profiles in Fig.14, it can be seen that the soil water recharging the shallow aquifer is tritium free or with very low tritium content at a certain depth of the soil core. If the aquifer is recharged only by this soil water infiltration flow, the groundwater should contain no tritium. However, the groundwater samples from the well in the nearby village Shanzuizi contain rather high tritium. It was 62.3 TU in 1988, and 34.4 TU in 1997. This fact implies, that the vertical infiltration of the soil water through the unsaturated zone at the sampling site of the core CHN/97 is not the main mechanism of the groundwater recharge. Perhaps, the runoff fraction of the water balance reaches the valleys and readily infiltrates. This means that despite the soil shows a water deficit, the aquifer is fully recharged.

8. Tritium profile of the core CHN/98

Zhang Zhigan et al. presented a tritium profile from loess deposits in a test pit in Shanxi province [6]. This test pit was in the same place as the core CHN/98. It had a section of 1m x 1m and depth 20 meters. Soil samples were collected every 0.40 m. The weight of each sample was about 5-6 kg. Water samples were obtained after distillation under 105°C. Direct liquid scintillation counting gives tritium contents of each samples. The tritium profile is shown in Fig. 15. The highest tritium content was at 5.6 meters in 1985, it infers a mean infiltration of 0.25 meters per year. Considering the mean water content is 19.3% for the soil column up to 6 meters, an annual recharge of 48 mm was obtained from this tritium profile.

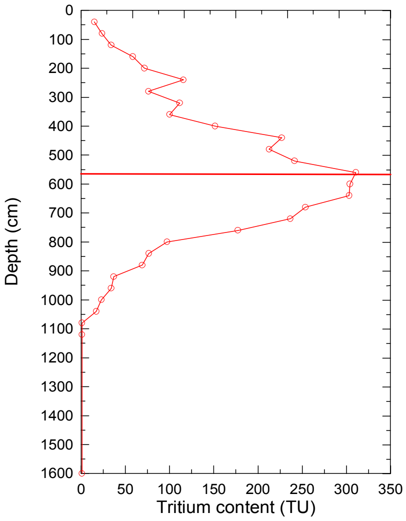

Fig. 15 Tritium profile of soil water samples in a test pit in Shanxi province in 1985 (After Zhang Zhigan et al. 1990).

Fig. 16 shows the tritium profile of the soil water from the core CHN/98. The tritium profile of the soil water for the core CHN/97 is also illustrated in the same scales for an easy comparison.. A clear tritium peak in the profile of CHN/97 is at the depth of 10.35 meters. The highest tritium content at the peak in 1997 is 230 TU. These two tritium profiles have the same shape, and the tritium peaks are at the same depth of the core. It seems that CHN/98 experienced more dispersion and the curve has been smoothed. The highest tritium content at the peak in 1998 is about 235 TU. As it has been noticed above, CHN/98 profile is consisted of two cores about 4 m apart from each other, and the depth 13.15 m is their joint point. As it can be seen from Fig. 16, that below 13.15 the curve of the core CHN/98 is shifted toward higher tritium content. It is difficult to be interpreted.

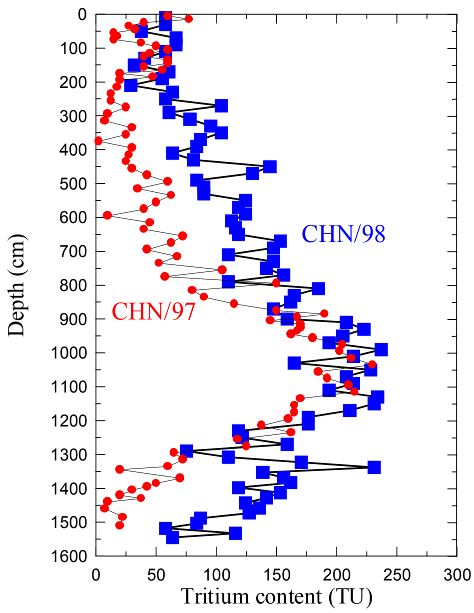

Fig. 16 Tritium profiles of the soil water from the core CHN/98 and CHN/97.

9. Stable isotopic profiles

Water samples were extracted from the soil by vacuum distillation and completion of the extraction procedure was confirmed. Isotope analyses for the water samples from the core CHN/97 was carried out in the IAEA lab. Isotope profiles of the soil waters for the core CHN/97 and CHN/98 are shown in Fig. 17.

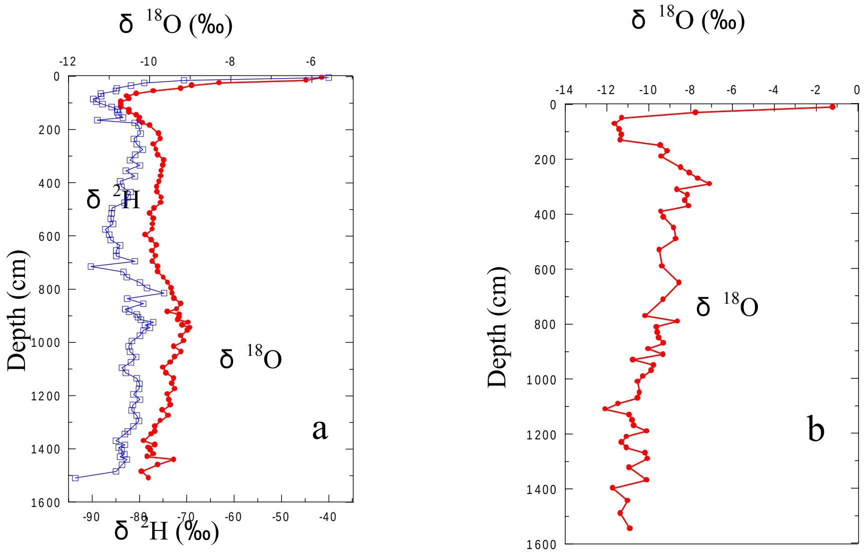

Fig. 17 Stable isotope variations in interstitial water from the core CHN/97 (a), Inner Mongolia, and core CHN/98 (b), Shanxi province.

The highest δ ^{18}O value of the soil water was on the top of the cores, but it decreased rapidly within the depth of 50 cm. This shallowest peak should be attributed to the evaporation of the last rainy episode. Nevertheless, on the δ ^{18}O-δ ^{2}H plot for the core CHN/97 (Fig. 18) the dot on the top of the core (depth 5 cm, dot in square mark) lies close to the meteoric water line. It seems that this soil water sample had not been enriched in heavy isotopes. This is because the core was taken on the next day after a heavy snowfall (7th of May, 1997). All other sample dots are on the line of evaporation with a slop of 4.35.

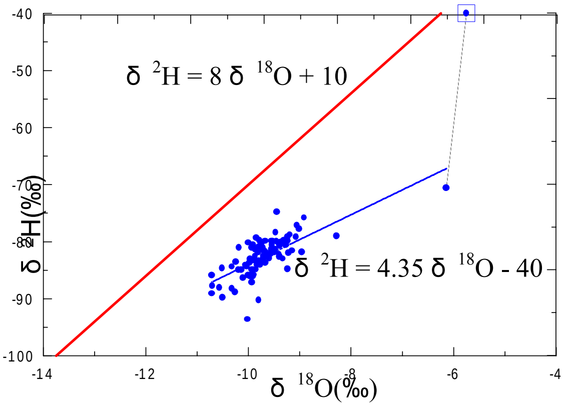

Fig. 18 δ ^{18}O-δ ^{2}H plot for the soil waters from the core CHN-97.

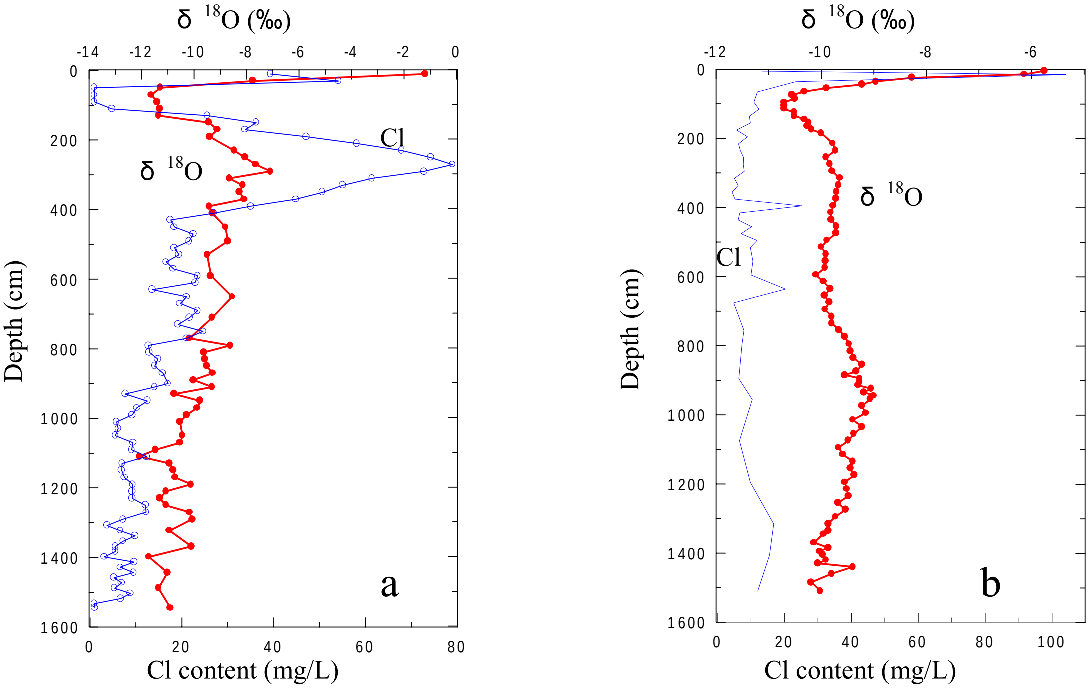

Fig. 19 Depth distribution of the δ ^{18}O value and the Cl content of interstitial waters for the core CHN/98 (a) and CHN/97(b).

Depth distribution of theδ ^{18}O value and the Cl content of interstitial water for the core CHN/98 is shown in Fig. 19a., in which two curves are similar and have peaks at the depth of 270 cm. It implies that changes inδ ^{18}O value and Cl content are caused by evaporation. We don't know if these two curves are similar also for the core CHN/97 (Fig. 19b), because the Cl content of interstitial water for the core CHN/97 was low in comparison with that from the core CHN/98, and it was difficult to be measured. Not only the Cl content of interstitial water, but also that of the rainwater (see Table 1) and groundwater (9.1 mg/L) was low in the case of the core CHN/97.

Table 1. Chloride concentration of precipitation in the wet season of 1997 in Wudan

Month (1997)	May	Jun	Jul	Aug	Sept	Mean
Rainfall (mm)	106.9	41.2	120.2	78.5	83.6	
Chloride concentration (mg/L)	1.93	2.28	2.10	2.63	2.28	2.2

10. Estimation of the recharge

10.1. Using tritium profiles

The tritium peak moved downwards 25 cm per year according to the tritium profile from core CHN/88, but that from core CHN/97 gives a value of 30 cm per year. Taking into account the water content of the soil is equal to 15.8 % and 15.6 % for cores CHN/88 and CHN/97 respectively, an average infiltration rate of 40 mm is obtained for the core CHN/88 up to 1988, and 47 mm/a is calculated as mean annual recharge for the core CHN/97 during the past 34 years.

The highest tritium content was at 5.6 meters in 1985 in the test pit. Thus a mean infiltration of 0.25 m per year in loess deposits in Shanxi province was obtained from the 1985 tritium profile. Taking mean water content as 19.3%, a value of 48 mm was obtained.

In core CHN/98, tritium peak is at the depth of about 10.50 m, it infers a mean infiltration of 0.30 m per year, a little bit higher than that obtained in 1985. Taking into account the volumetric water content of 22.5%, an average recharge of about 68 mm is calculated for the past 35 years.

10.2. Using chloride profiles

According to C.B. Gaye and W.M. Edmunds [3], the recharge flux R of chloride concentration C_R can be expressed by the equation:

$$R = PC_P / C_R \qquad (1)$$

Where

R is the infiltration recharge (mm),
P is the annual rainfall (mm),
C_P is the chloride concentration of the precipitation (mg/L),

and C_R is the chloride concentration of the interstitial water (mg/L).

In equation (1), it is assumed that the surface runoff is negligible, and precipitation is the only source of water input.

In the case of core CHN/97 of Inner Mongolia, annual precipitation of P = 360 mm, which is obtained from data of the Wudan Meteorological Station (12 km to the north of the sampling site). The mean chloride concentration C_R of 9.3 mg/L is taken from the chloride profile excluding the first 1.5 m. A weighted mean value of rainfall chloride, C_P, 2.2 mg/L is taken from data of precipitation samples collected in Wudan Meteorological Station in 1997 (Table 1). Then a value of R = 85 mm can be calculated as mean value of recharge.

In the case of core CHN/98, P = 550 mm/year, C_R = 19.5 mg/L was obtained as mean value of the soil samples in the profile excluding the first 1.5 m. C_P = 10.2 mg/L was taken from data of precipitation samples, collected in 1984 in Loufan Meteorological Stations, which is located about 90 km from the sampling site CHN/98 (Table 2). A value of recharge R = 288 mm was estimated by the same calculation.

Table 2. Chloride concentration of precipitation of 1984 in Loufan

Month (1984)	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Mean
Rainfall (mm)	47.0	110	56.5	35.4	8.2	4.1	9.3	
Cl concentration (mg/L)	10.3	10.3	10.1	8.56	10.9	11.7	14.3	10.2

It should be noticed, that in the case of core CHN/97, the recharge value derived from chloride profile is higher than that from tritium profile. As for the core CHN/98, the recharge estimated by the chloride method is much higher than that by the tritium profile. This is probably because the assumption for the equation (1) in loess areas is not true and the surface runoff could not be neglected. The tritium content of the ground water in both sampling sites is rather high and close to that of the rainfall. Besides, the tritium content of the interstitial water at the depth more than 15 m is very low. These facts infer a fast infiltration in loess areas in recharging groundwater aquifers and the vertical infiltration through the unsaturated zone must not be the only the mechanism of recharge.

10.3. Using stable isotopes

The stable isotope composition of soil water collected in arid zones has been used to estimate the evaporation rate. While in humid areas it has been shown to be amenable to interpretation in terms of infiltration rate.

Fig. 20a shows rainfall distribution in Wudan County in the period of 1951–1997 (data from the Wudan Meteorological Station, located at 12 km to the north of the sampling site CHN/97). Years with higher rainfall, 1954, 1969, 1985 and 1991 are marked with asterisks. Fig.20b is depth distribution of water content for the core CHN/97. Years of recharge, obtained from an infiltration rate of 30 cm / year, are marked along the abscissa instead of the depth. Fig. 20c is $\delta\ ^{18}O$ profile of soil water for the core CHN/97. It seems that in the case of core CHN/97 from Inner Mongolia, the $\delta\ ^{18}O$ value of interstitial water is correlated to the water content, implying that the $\delta\ ^{18}O$ profile of the interstitial water is controlled mainly by the infiltration rather than evaporation. It should be noticed that the infiltration rate is dependent not only on the amount of precipitation, but also on the distribution of the annual rainfall.

Sometimes higher rainfall leads to a higher surface runoff rather than more infiltration through the unsaturated zone. Nevertheless, it can be seen from Fig. 20a and 20b, that soil samples with higher water content are in years of higher rainfall.

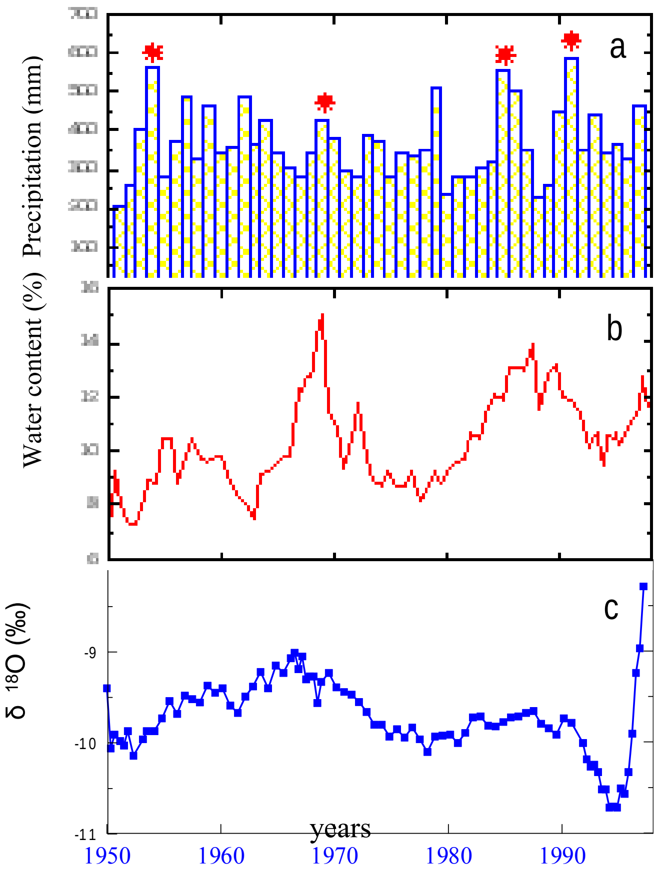

Fig. 20 a Annual precipitation in the sampling site of core CHN/97 (mm), 20b :water content (%) and 20c:δ ^{18}O value (‰) for the soil water along the core CHN/97.

Besides, interstitial water recharged during the wetter years are more enriched in heavy isotopes than those recharged during the drier years (see Fig. 20b and 20c). According to C.B. Gaye and W.M. Edmunds, years with higher rainfall will tend to be less enriched in heavy isotopes than those with low rainfall. Obviously, in the case of northwestern Senegal, years with higher rainfall are corresponding to lower evapotranspiration. While in the case of Inner Mongolia, higher rainfall implies higher evaporation, and interstitial water tends to be more enriched in heavy isotopes.

If the correspondence between abscissas of these three figures (Fig. 20a, 20b and 20c) is acceptable, the rate of infiltration for the core CHN/97 would be 0.30 m/year, the same value as that from the tritium profile.

In the case of Shanxi province (core CHN/98) the δ ^{18}O value is correlated with the chloride content of interstitial water (Fig. 19a). It infers the evaporation characteristics of the δ ^{18}O profile. Fig. 21a and 21b are depth distribution of water content for cores CHN/97 and CHN/98. These two sampling sites are all located in northern China and in similar semi-arid climate conditions. Although they are about 800 km from each other. water content curves are similar, as it can also be seen from Fig. 21 a,b.

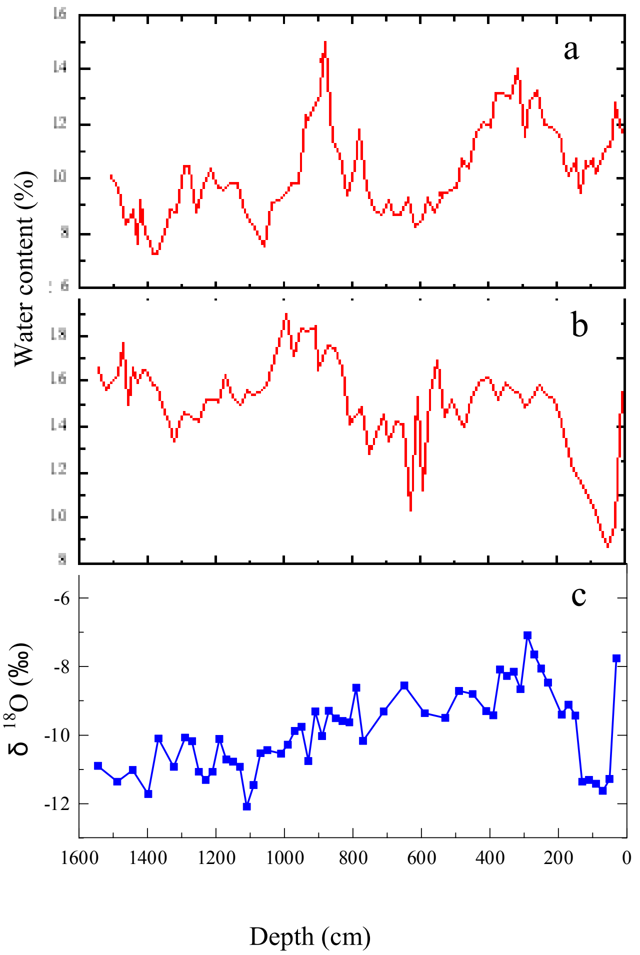

Fig. 21a Water content (%) along the core CHN/97.
21b Water content along the core CHN/98.
21c δ ^{18}O value (‰) for the interstitial water along the core CHN/98.

Fig. 21c is δ ^{18}O profile for the core CHN/98. Positive correlation between water content and δ ^{18}O values for the core CHN/98 is observed only in the first 8 meters of the core (Fig. 21b and 21c). In this depth interval two peaks can be recognized and they are at the same depths as for the core CHN/97. So the infiltration rate estimated from the stable isotope will be also about 0.30 m/year. After 8 metersδ ^{18}O values of interstitial water are not correlated to the water content.

11. Main conclusions

Pore-water tritium profiles from the loess unsaturated zone in Inner-Mongolia and Shanxi province of China show clearly defined peaks, which could only have originated from the fallout in the period of frequent thermonuclear weapon testing around 1963. These profiles indicate that loess deposits are highly homogeneous, in which piston-flow model is the dominant process for soil water movement. Average infiltration rate obtained from these profiles is 0.30 m /year for both sampling sits. This value is much less than that obtained from the tritium profiles of Chalk unsaturated zone (1 m / year).

The annual recharge derived from tritium profile for the core CHN/97 is 47 mm per year, while that from chloride profiles is 85 mm per year. It means that in loess deposits a fraction of rainfall does not infiltrate downward through the loess unsaturated zone, and the values of annual recharge derived from the chloride profiles are higher than those from the tritium profiles.

It is difficult to make a numerical calculation of recharge based on stable isotope data. Nevertheless, the depth distribution of stable isotopic ratios is correlated well with the water content profile. This qualitative signal helps to confirm the results obtained by tritium method.

Values of infiltration recharge in semi-arid loess areas in northern China obtained using different methods are summarized in Table 3.

Table 3. A comparison of values of recharge

Core	CHN/97	CHN/98
Depth of the core (m)	15.15	15.50
Depth of the ^{3}H peak of 1963 (m)	10.35	10.50
Max ^{3}H content (TU)	230	235
Infiltration rate (m/a)	0.30	0.30
Vol. water content (%)	15.6	22.5
Mean recharge by ^{3}H and δ^{18}O	**47**	**68**
^{3}H content (TU) of the rainfall	27.4 TU in 1997-05-07	54 TU in 1984
^{3}H (TU) in ground water	34.4	43.4
Annual precipitation (mm)	360	550
Rainfall Cl^- (mg/L)	2.2	10.2
Soil water Cl^- (mg/L)	9.3	19.5
Ground water Cl^- (mg/L)	9.1	49.7
Mean recharge by Cl (mm)	**85**	**288**

From above estimations, one can conclude that vertical infiltration through the unsaturated zone accounts for 12% - 13% of the annual precipitation in both sampling sites. However, the tritium content of the aquifer is high, despite the water table is at a depth of more than 20-30 m, and the soil water is almost tritium free below the depth of 15 m. Therefore, vertical infiltration on soil in semi-arid loess region, perhaps, is not the main mechanism of recharge. It seems that some part of the runoff fraction of the water balance reaches the valleys and readily infiltrates. This means that despite the soils show water deficit because of high evaporation, the aquifer is recharged better than expected. These findings may provide additional guidelines for regional water management.

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Application of isotopes and chemistry in unsaturated zone in arid areas of Rajasthan, India

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Abstract. Isotopes and chemistry of unsaturated zone soil profiles in Saraf ki Dani, Sihania and Lakrasar site in Barmer district of western Rajasthan, and precipitation samples collected at Chohtan, the nearest meteorological station, have been used to study groundwater recharge and to characterise the behaviour of contaminants in the subsurface. Soil water was extracted by vacuum distillation and analysed for ^{2}H and ^{18}O, whereas elutriation methods were used for chemistry. Based on the observed chloride profiles, groundwater recharge rates are estimated to be ~10 to 18 mm per annum for the above sites. $\delta^{18}O$ profiles at Sihania and Lakrasar (1999), reveal depleted $\delta^{18}O$ values observed at a depth of ~2 m, possibly due to an episode of heavy rains during 1998. Depthwise distribution of of F^-, SO_4^{-2} & NO_3^- at Sihania site II (1999) and $\delta^{18}O$ signatures confirm that evaporative concentration occurs during dry periods. Enrichment of NO_3^- in the profiles may be related to fixation of nitrogen by leguminous plants.

1. Introduction

For proper management of groundwater resources, information on direct recharge of precipitation to the groundwater is important particularly in arid areas. The isotopic composition and chemistry of water infiltrating through the unsaturated zone to the groundwater body could be used to determine the groundwater recharge [1] [2] [3].

The aim of the project was to obtain profiles of isotopes (^{2}H, ^{18}O) and chemical species (Cl^-, NO_3^-, F^- etc.) in the unsaturated zone to study groundwater recharge and information on contaminant movement in parts of Western Rajasthan.

This report presents the studies carried out under the CRP from 1996 to 1999. In the following sections a) description of the study areas, b) sampling for precipitation, unsaturated zone sediment and groundwater, c) analytical procedure for isotopes and chemistry and d) interpretation and recharge estimation are presented.

2. Description of the study area

The study areas are located in Barmer district of western Rajasthan (Fig.1).

A geological section covering the study areas is shown in Fig.2. It is evident from the section that basement crystallines are encountered at shallow depths in Chohtan and further southwards the basement is encountered at depths > 200 m. The thickness of the quarternery sediments is therefore more in the southern part. The quarternary sediments generally consists of wind blown fine grained sand forming top layer and older alluvium below. The sediments belonging to the old alluvium form 2 layers, the upper layer consisting of fine to coarse sand with calcretes, gravel and clay and the lower layer predominantly consists of clay with some lenses of coarse sand, gravel and calcretes.

The formation in the southern parts provides good yield as observed from high discharges from tube wells located in these areas [4].

The climate in the study areas is arid. The rainfall is generally low and erratic. The maximum amount of rainfall in the region is received during southwest monsoon period i.e. from June to September.

The sites selected were

(a) Alamsar (Saraf ki Dani)

(b) Sihania

(c) Lakrasar

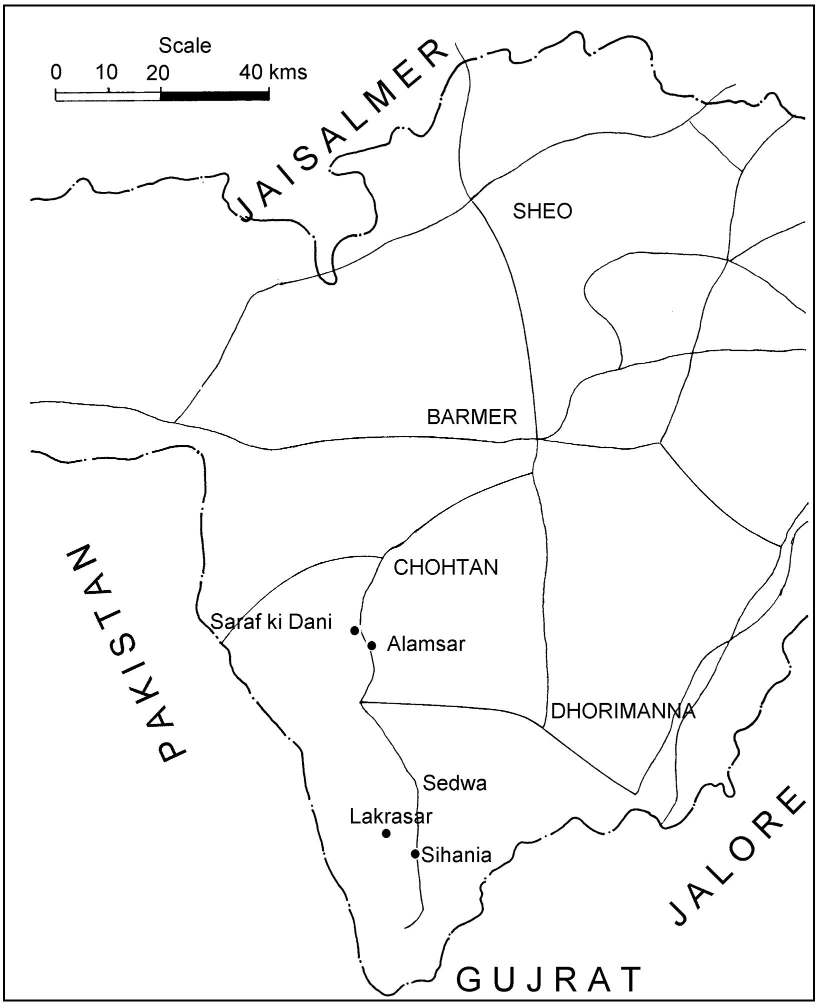

Fig. 1. Location of the study areas.

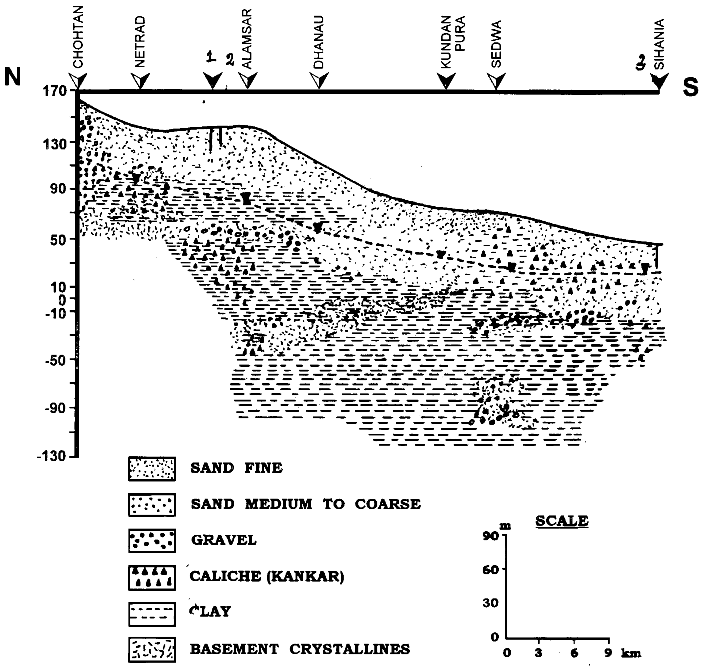

Fig. 2. Geological section from Chohtan to Sihania in Barmer district.

The sites were selected from the study of the lithologs of the boreholes in these locations.

The lithology of the tube well site in Alamsar near site (a) and in Sihania near site (b) are as follows:

Alamsar Tube Well

S.No.	Lithology	Depth (m)
1.	Fine grained wind blown sand brown in colour	0 - 6.0
2.	Very fine grained sand with mixed with big pieces of Calcrete	6 - 30.0
3.	Fine grained sand brown in colour	30 - 42.0
4.	Sand with Calcrete brown in colour	42 - 54.0
5.	Sandy clay with calcrete brown in colour	54 - 91.0

The water table is at 63 m. The discharge of the tube well is ~ 30 m^3/day.

Sihania Tube Well (near Public Health Engineering Department Campus)

S.No.	Lithology	Depth (m)
1	Fine wind blown sand earthy appearance having some mica metler	0 - 2.0
2.	Very loose sand having fine pieces of quartz	2 - 17.0
3.	Sand, dark brown in colour having small pieces of calcrete	17 - 32.0

The water table is at 23 m and the discharge of the public well in Sihania is 10 m^3/day.

The vegetation in the study areas is generally sparse. Crops such as mustard, Isabgol, cummin seed etc. are grown during the rainy season. The human activity in the area is generally farming, cattle breeding, growing sheep, goat, camel etc.

The nearest IAEA Global Network of Isotopes in Precipitation (GNIP) station is New Delhi. Local rainfall data was collected from Chohtan which is ~ 25 km from Alamsar (Fig.1). The rainfall data since 1957 to 1996 is presented in Fig.3. Long term mean rainfall in Chohtan was 240 mm.

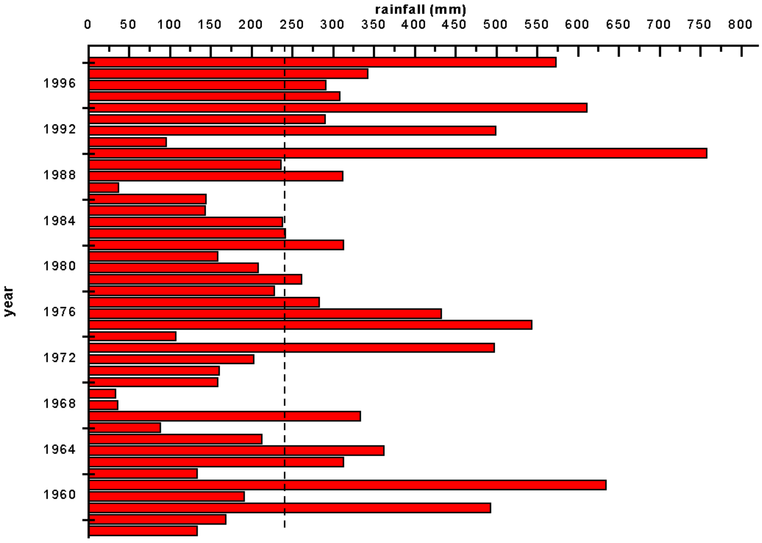

Fig. 3. Rainfall data in Chohtan station, Barmer district.

3. Sampling for precipitation, unsaturated zone sediments and groundwater

(I) Precipitation samples were collected using a raingauge at Met. station at Chohtan. Precipitation samples were also collected at Met. station in Barmer town. The samples were analysed for ^2H, ^{18}O and chemistry.

(ii) Unsaturated zone sediments

(a) Soil cores were collected using a Dormer International Hand Drilling unit. The first set of cores were collected at Saraf Ki Dani during 1997. Samples were collected upto a depth of about 12 m, at an interval of 25 cm. The second set of cores were collected at Sihania site during 1998. Coring was attempted upto the water table i.e. 22.6 m. However, due to the presence of rubbles and calcretes at depths > 15 m, coring had to be stopped after 15 m. Cores were collected at an interval of 50 cm. Third set of cores were collected at another location at Sihania site during 1999. At this site again, coring could be carried out only upto 15 m depth. Finally the fourth set of cores were collected at Lakrasar upto ~ 7 m depth. The core samples were processed and soil water extracted were analysed for isotopes and chemistry.
Groundwater samples were collected from open wells and tubewells at Saraf Ki Dani, Sihania and Lakrasar for isotopes and chemical analyses.

4. Analytical procedure for isotopes and chemistry

Environmental isotopes ^2H and ^{18}O:
Soil water from soil cores was distilled under vacuum at 100°C. ~ 100 % of soil water was collected. The soil water was analysed for δ^2H and $\delta^{18}O$ using a 602E VG ISOGAS mass spectrometer in BARC

δ^2H and $\delta^{18}O$ of precipitation and groundwater samples were also analysed in a similar fashion as soil water.

Determination of moisture content and chemistry of soil water moisture:
Unsaturated zone soil samples were taken and moisture content determined by gravimetric method.

Chloride, fluoride, nitrate and sulphate content of soil water:
50 g of the soil sample was taken in a 250 mm flask and ~ 25 ml of distilled water was added to it. The flask was shaken well and kept as such of 2 -3 hours. The leachate was decanted into polythene tubes and centrifuged for ~ 10 minutes. The supernatant was collected and assayed for chloride, fluoride, nitrate and sulphate.

The chloride was measured using the spectrophotometric method [5] as well as using Dionex 500 ion chromatograph. The remaining species (flouride, nitrate and sulphate) were measured only on ion chromatograph. For ion chromatograph measurement Ion Pac As 11 in combination with guard column AG 11 were used for the separation of the ions. ED 40 electrochemical detector in conductivity measuring mode was used for the detection of the ions. The precision of measurement by spectrophotometric method was 0.5 ppm for Cl^- whereas with ion chromatograph it was 0.4, 0.25, 1 and 1.5 ppm respectively for Cl^-, F^-, NO_3^- and SO_4^{-2}

5. Results

5.1. Precipitation samples at Chohtan and Barmer

δ^2H, $\delta^{18}O$ and Chemistry of precipitation samples at Chohtan and Barmer were analysed. The results obtained are as follows:

weighted average of $\delta^{18}O$	-3.4‰ (Chohtan)
Average chloride content	2 ppm (Chohtan)

5.2. Soil water samples

(A) Saraf Ki Dani Site (1997)

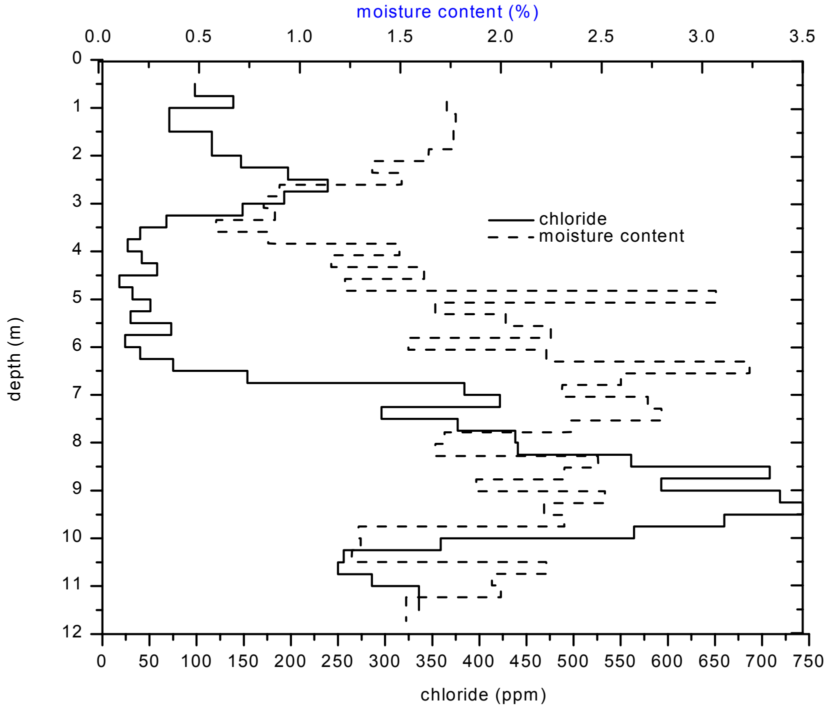

Fig. 4. Moisture content and Chloride profile at Saraf Ki Dani Site (1997).

(a) The moisture content profile (Fig. 4) shows low moisture contents at depth 2-4 m (~ 1 % (w)) and below 4 m the moisture content varies from 1.5 to 3 %.

(b) The chloride content profile (Fig 4) shows steady state value of ~ 50 ppm at depths of 4 to 6 m. Direct recharge using the chloride balance method [1] works out to be 9.6 mm per year. (The chloride content increases to a maximum of 750 ppm at a depth of 9 m)

(B) Sihania Site - I (1998)
The moisture content profile (fig.5) show low moisture content (~ 1 %) in the top 1 m and then increases to 3.5 % at a depth of ~ 3 m. After this there is a decrease upto 2% at a depth of ~ 4 m. Subsequently the moisture content steadily increases upto 4% at depths between 10 m to 14 m.

- The δ^{18}O profile (fig.5) shows enriched values of 0‰ at a depth of about 4 m and then a steady depletion to -7‰ at a depth of ~ 6 m and subsequently shows enrichment and below 10 m gives steady value of about -4‰.
- δ^{2}H - δ^{18}O plot show an equation of $\delta^{2}H = 7.0\ \delta^{18}O - 5.7$ ($r^2 = 0.96$, n = 17). This line deviates from the meteoric water line (Fig. 6).

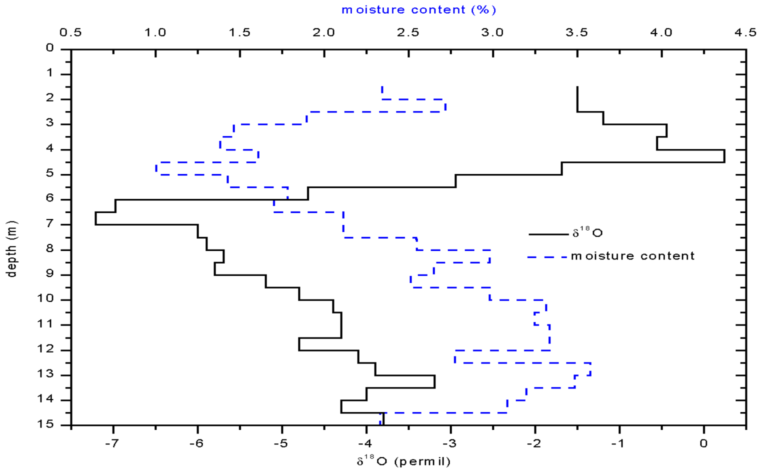

Fig. 5. Moisture content and ^{18}O profile at Sihania I (1998).

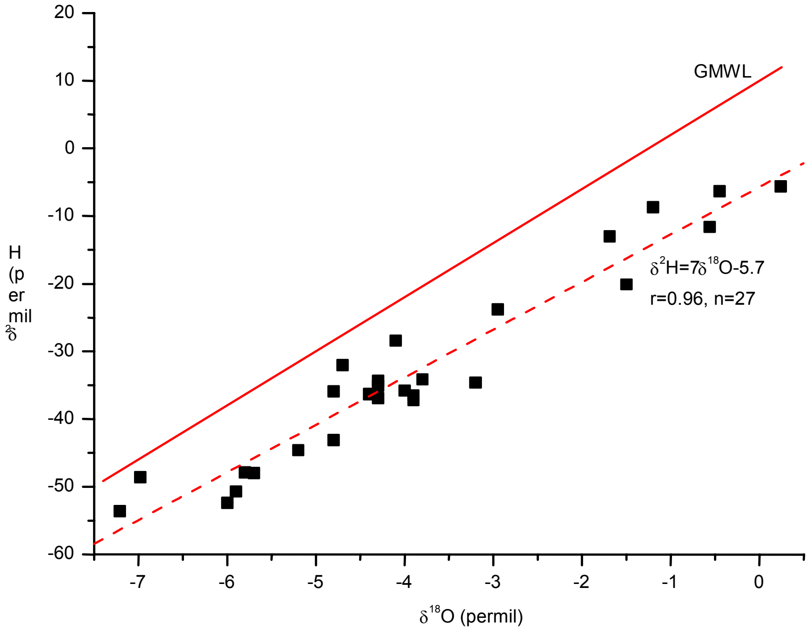

Fig. 6. δ^2H - δ^{18}O- plot of soil water samples at Sihania II (1998).

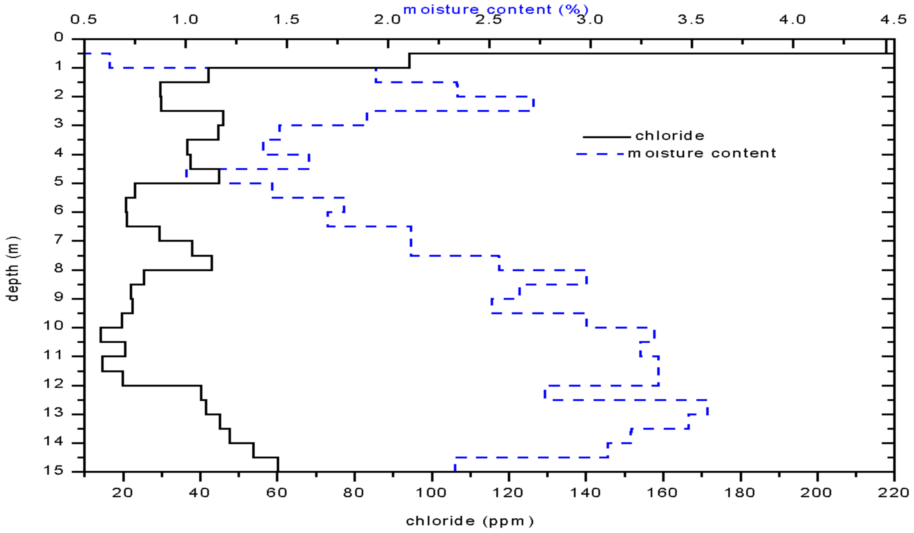

Fig. 7. Moisture content and Chloride profile at Sihania I (1998).

Chloride profile (fig. 7) show steady state value of 33 ppm. Direct recharge works out to be 14.5 mm.

(A) Sihania site II (1999)

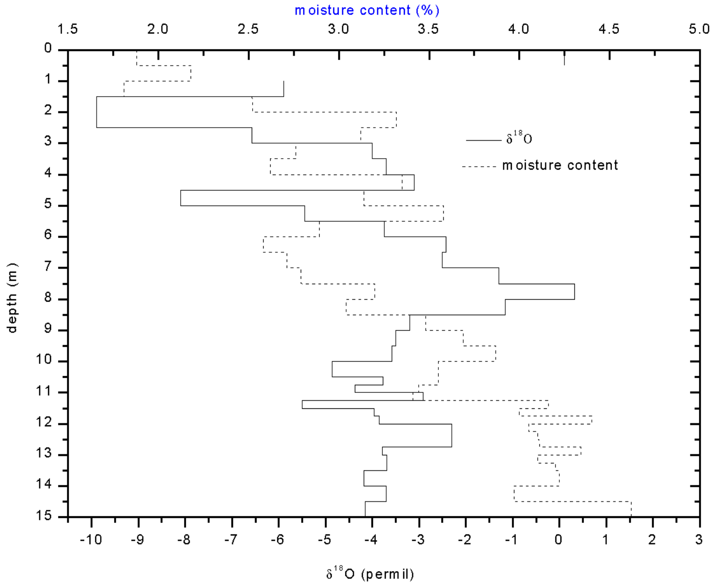

Fig. 8. Moisture content and ^{18}O profile at Sihania site II (1999).

(i) The moisture content of soil cores during April 1999 (fig.8) show low moisture content (~ 2%) in the top 1 m where as it increases to around 3.5% at 5 m. Subsequently the moisture content increases upto 4% below 12 m.

(ii) The $\delta^{18}O$ profile (Fig. 8) show enriched values in the top 1 m as expected and then at depths of 1.5 to 2.5 m show depletion upto -9.9‰. Depleted $\delta^{18}O$ at shallow depths could be due to heavy rains during 1998 rainy season. Subsequently the profile shows another depleted $\delta^{18}O$ signature at ~ 5 m and enrichment to 1.7‰ at depth of 8 m. After which the $\delta^{18}O$ profile shows steady value of ~ 4‰.

(iii) The δ^2H - $\delta^{18}O$ plot (Fig 9) show 2 groups of samples, one group with equation $\delta^2H = 4.7\delta^{18}O - 21.6$ ($r^2 = 0.96$, n =15) showing evaporation effect and the other group having an equation $\delta^2H = 6.1\ \delta^{18}O - 6.3$ ($r^2 = 0.88$, n = 11) showing less evaporation effect. Stable isotope could be used to distingush between high and low evaporation within the profile.

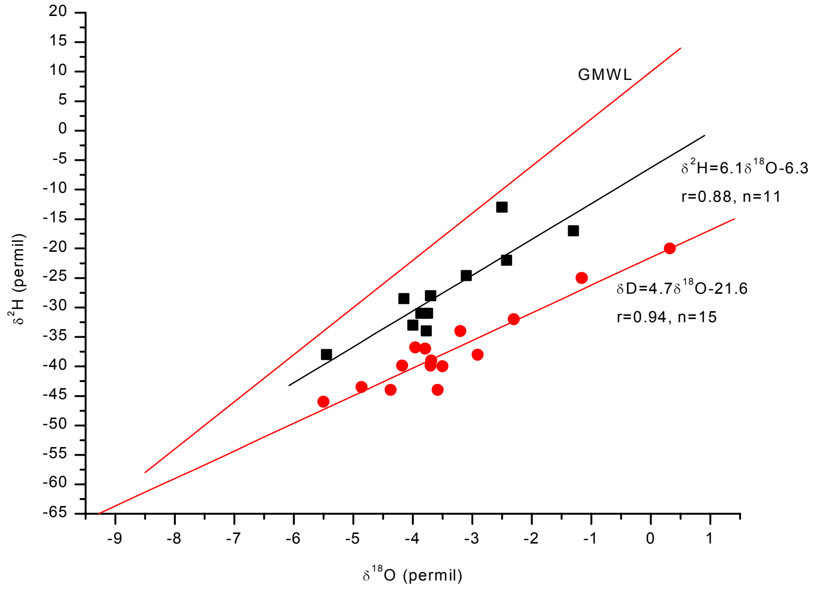

Fig. 9. δ^2H- $\delta^{18}O$ plot of soil water samples from Sihania site II (1999).

(iv) Chloride profile (fig.10) shows a steady state value of 26.5 ppm. Direct recharge works out to be ~ 18 mm.

(v) Environmental NO_3^-, SO_4^{-2} and F^- were plotted with respect to depth and presented in Fig.11. The NO_3^- profile shows peak value of ~ 100 ppm at 7.5 m and 12 m depth. The source of NO_3^- is to be identified using $\delta^{15}N$. The enrichment of Nitrate is possibly due to fixation of Nitrogen by leguminous plants [6]. The SO_4^{-2} profile shows peak concentration of ~ 100 ppm at the top 25 cm and subsequently show an average value of ~ 25 ppm. The F^- profile show peak values of ~ 12 ppm at a depth of ~ 8 m.

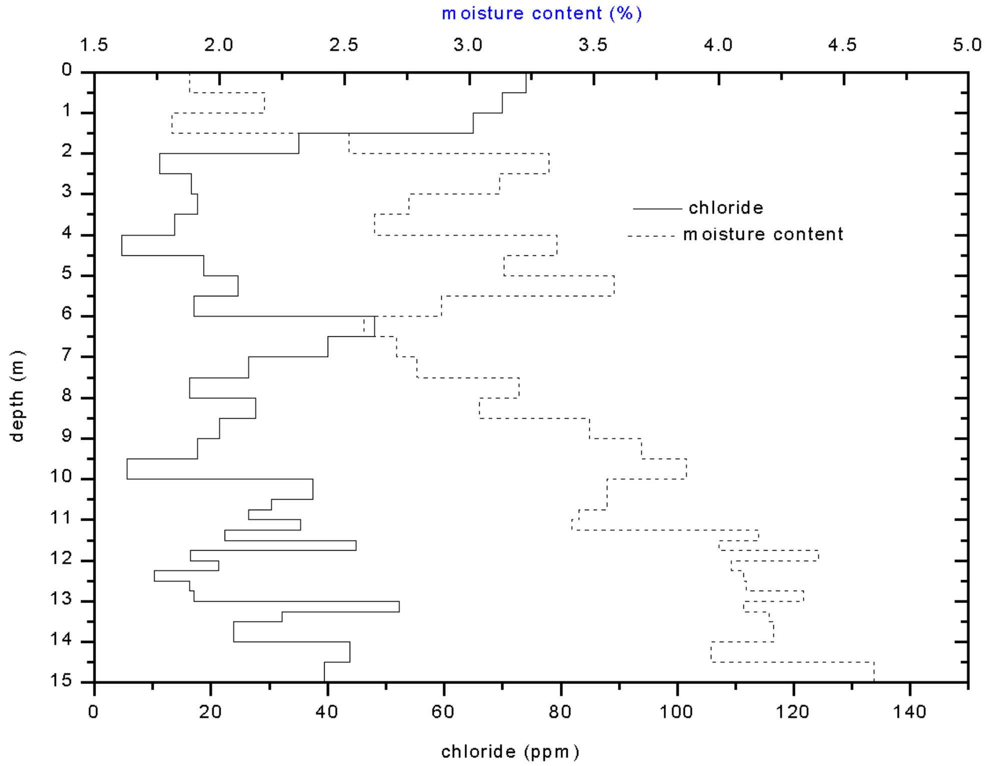

Fig. 10. Chloride, moisture content vs depth, Sihania site II (1999).

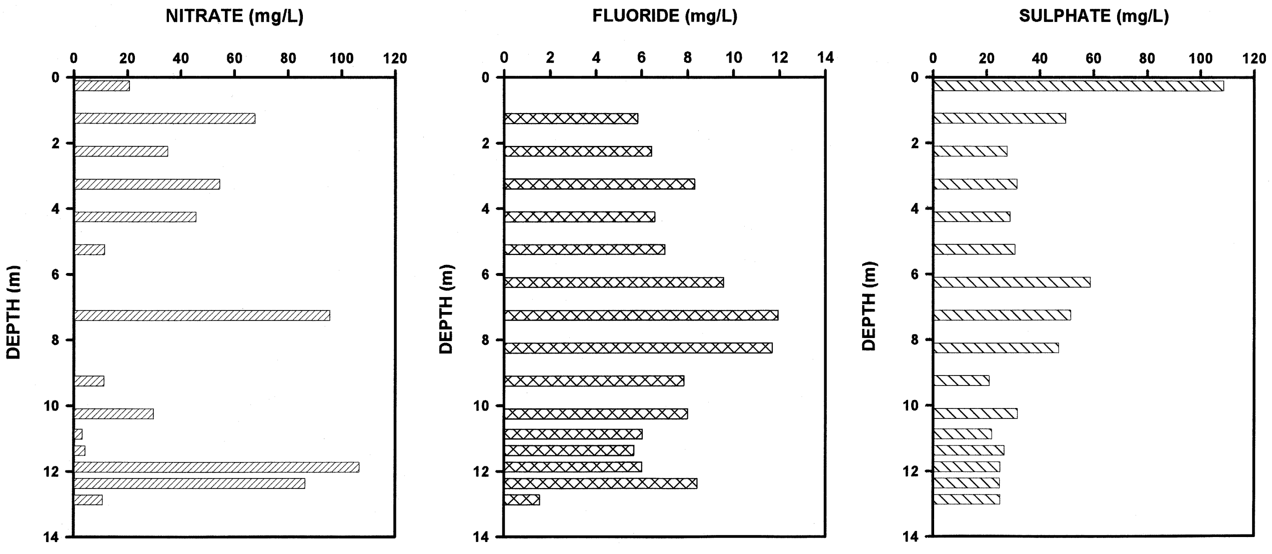

Fig. 11. Depth-wise distribution of nitrate, sulphate and fluoride at Sihania site II (1999).

(D) Lakrasar site (1999)

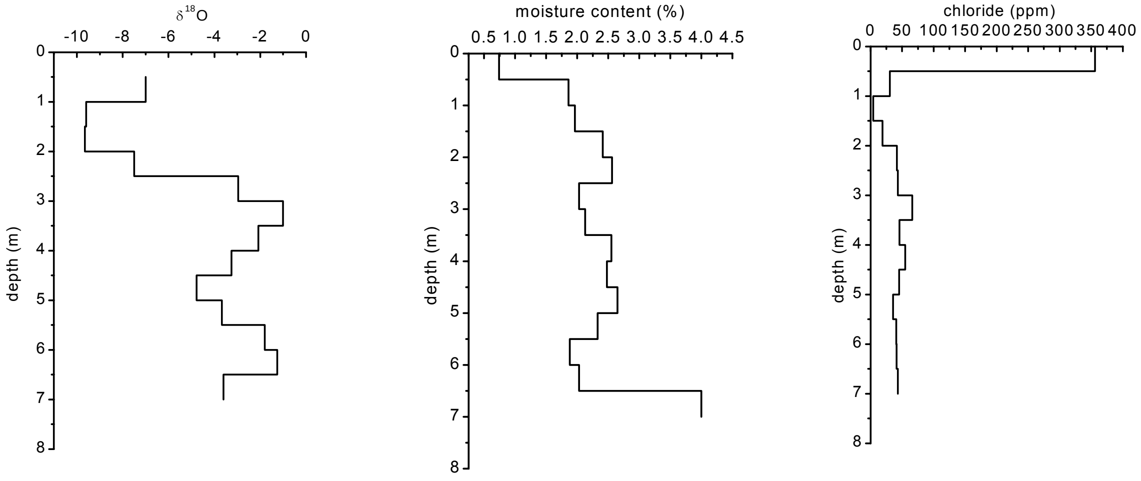

Fig. 12. δ^{18}O, moisture content and chloride vs depth, Lakrasar site (1999).

The δ^{18}O, moisture content and chloride profile (fig.14) at Lakrasar show similar trends as observed in Sihania site.

The average chloride content in the profile is 39.3 ppm. The recharge valve works out to be 12 mm/year.

The δ^{18}O profile show depleted values at depth of ~ 1.5 m to 2 m from the surface as seen in Sihania site.

6. Discussion of the results

(I) Groundwater recharge from Chloride

The groundwater recharge computed profile for Saraf Ki Dani , Sihania and Lakrasar sites are given in table below:

S.No.	Site	Recharge (mm) (± 0.5 mm)
1.	Saraf Ki Dani (1997)	10
2.	(a) Sihania (1998)	14.5
3.	(b) Sihania (1999)	18
4.	Lakrasar (1999)	12

The recharge value at Saraf Ki Dani is lower compared to other sites as the soil is composed of fine grain sand. In Sihania and Lakrasar with recharge ranges from 12 - 18 mm. The variation of recharge at 2 sites in Sihania separated by ~ 50 m could be due to matrix conditions in the unsaturated zone.

(ii) δ^{18}O profile.

The δ^{18}O profile at Sihania and Lakrasar show depleted values at depths of ~ 2m. The depleted values could be due to heavy rains during 1998.

(iii) Nitrate, Sulphate and Fluoride profiles

The depthwise distribution of anions (NO_3^-, SO_4^{-2}, F^-) shown in figure 11, show peak values ~ 8 m below surface. Nitrate profile show an additional peak at ~ 12 m. Comparison of these profiles with $\delta^{18}O$ profile show that enrichment in $\delta^{18}O$ at ~ 8 m depth. This indicates that the higher concentration of anions observed at ~ 8 m could possibly be due to concentration due to evaporation.

7. Conclusions

(a) The groundwater recharge at Saraf Ki Dani, Sihania and Lakrasar in Barmer district range from ~ 10 to 18 mm.

(b) From $\delta^{18}O$ profiles at Sihania and Lakrasar depleted values observed at shallow depths of ~ 2 m could be due to heavy rain during 1998. Stable isotopes could be used to distingush zones of high and low evaporation within the profiles.

(c) Peak value at ~ 8 m observed in depthwise distribution of NO_3^-, SO_4^{-2}, F^- at Sihania indicate evaporative concentration during dry period as confirmed by comparing it with $\delta^{18}O$ profiles. Enrichment of NO_3^- in the profile could possibly be due to fixation of Nitrogen by leguminous plants.

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General hydroisotopic study of direct infiltration and evaporation process through the unsaturated zone in Damascus oasis, Syrian Arab Republic

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Abstract. Damascus oasis plays an important economical and environmental role in the city life because it presents the surrounding green places and the groundwater is the main sources for irrigation. In this study we will focus on the unsaturated zone in Damascus oasis. Environmental isotopes as ^{18}O, ^{2}H and ^{3}H are considered one of the most important techniques that are used in unsaturated zone study in order to study the water movement mechanism, estimate the effective velocity, the rate and spatial variations of the direct infiltration through this zone.The Deuterium profile allow to estimate the direct evaporation rate, and it is observed that the evaporation in the eastern part of the studied area is 5-6.5 mm/y. The Tritium peak of profile that is belonging to the atmospheric nuclear tests at the beginning of the sixties indicates the effective infiltration velocity of 27.8 mm/y. The effective porosity was estimated about 6.5% and the permeability parameter is $0.6*10^{-10}$ m/s. The direct infiltration rate was estimated by the chemical Chloride balance in the studied profiles in addition to their spatial distribution where it was distinguished between the eastern area where the direct infiltration is less than 2 mm/y characterized by very fine clay soils and western area where the direct infiltration rate is more than 2 mm/y with sandy soils. It is thought that the lower part of the unsaturated zone indicated the direct infiltration rate about 3.5 mm/y, under more wet climatic conditions where the rainfall was about 423 mm/y, this wet period was extended from about 432 y to more than 760y ago.The Nitrate concentration variation with depth indicated that unsaturated zone play important role as purification zone, and the groundwater which has more than 5 m depth is prevented from pollution, whereas the groundwater that has less than 5 m depth is more prone to pollution by high concentration of Nitrates.

1. Introduction

Damascus Oasis, which extends over 1200 Km^2 to the south of Damascus City, plays a main economical role in the agricultural production Fig.1. To the north and north west of it, there is Kassioun mountain (1150 m), to the south and southwest there is Maneh mountain (950 m), Badieh plate forms the eastern and southeastern borders. The oasis has mean altitude about 650 m.a.s.l. and varies from 600 m near Oteibeh lake to 750 m in Al-Mazzeh. This oasis represents the lower part of Barada and Awaj basins where the upper parts lies in the Anti-Lebanon and Haramoun mountain (2814 m) in the northwest.

Many hydrological and hydrogeological studies were conducted to determine the sources of the surface water, in one hand, and the groundwater that presents 75% of water resources used in irrigation in other hand. The estimation of some water balance components as evaporation and direct infiltration rate through the unsaturated zone is unprecise this is attributed to the difficulty in applying the conventional methods in arid and semi arid region [1]. Using isotope techniques as 18-O, Deuterium and Tritium is the most useful techniques in this regard. Abou Zakhem & Hafez, 1995 [2] used this technique in the study of evaporation and direct infiltration through the unsaturated zone in Damascus Oasis and study the water mouvement mechanism by performing two isotopic profiles in this zone. This study is a completion study in order to evaluate the direct infiltration rate accurately, the spatial distribution through many profiles, estimate the Chloride balance, detect the Tritium peak that occurred in the period of atmospheric nuclear tests at the beginning of sixties to evaluate the infiltration velocity, and use the unsaturated zone as an archive to study the paleoclimates and the paleohydrological conditions that feed the aquifers.

This study was done in co-operation within IAEA project CRP, entitled "Isotope based assessment of groundwater renewal and related anthropogenic effects in water scarce area." nº SYR / 9251.

In this paper a geological, hydrological, hydrogeological, climate and isotopic studies were performed in addition to lab and fieldwork.

2. Geology

In the middle of Kassioun mountain anticline, the (Toronian-Campanian) limestone and calco-dolomite rocks expose (Fig.1). The eastern side of the anticline was affected by vertical fault (NE-SW) which is of a regional importance. Its slope ranges between 20º-30º in the NW and 70º- 80º in the SE.

The Paleogene formation is exposed on the border of the anticline represented by limestone, marly limestone and marls.

The Neogene is characterized by continental rock debris consisting of conglomerates, sand fine, sandy marl and silt covering the depression of Deemas desert reaching the north western part of Damascus.

The Quaternary rock debris fills in Damascus depression, represented by proluvial and alluvial deposits with gravels and big sized sands. Eastwards, sediments grain size decrease to become clayey, sandy and fine loamy lacustrine near Oteibeh lake presenting the most recent Quaternary. To the south and southeastern rims of the basins, Neogene and Quaternary basalt outcrops [3].

3. Hydrology and hydrogeology

Barada and Awaj rivers represent the main rivers in the hydrographic network where Barada is fed from several Karistic springs located on high mountains, in particular Barada spring with average discharge (3.12 m^3/s) and Figeh spring (7.7 m^3/s) which is used for drinking water supply purposes in Damascus city. Whereas, the Awaj rivers is originated from Haramoun mountains. The mean discharge of Barada river under natural conditions is 150 $M.m^3/y$ and for Awaj river is 100 Mm^3/y (The Russian report, 1986) [4].

Barada river has seven estuaries that are used for irrigation purpose in eastern part of Damascus oasis (Ghouta), whereas Awaj river is used for irrigation in the western part of Ghouta and Kisswa region. Barada and Awaj rivers are terminated in Oteibeh and Hijaneh lakes respectively, which are considered as closed terminal lakes in the lower part of the basin. However, these rivers reach the lakes during flood periods only.

In Damascus depression, the Quaternary formation has very important aquifer invested by 25000 wells. The depth of the water level varies from 1–6 m in the western part of depression and reaches 35–50 m depth in the eastern part of it. It forms two pesometric depression resulted from extensive investment (Fig.2).

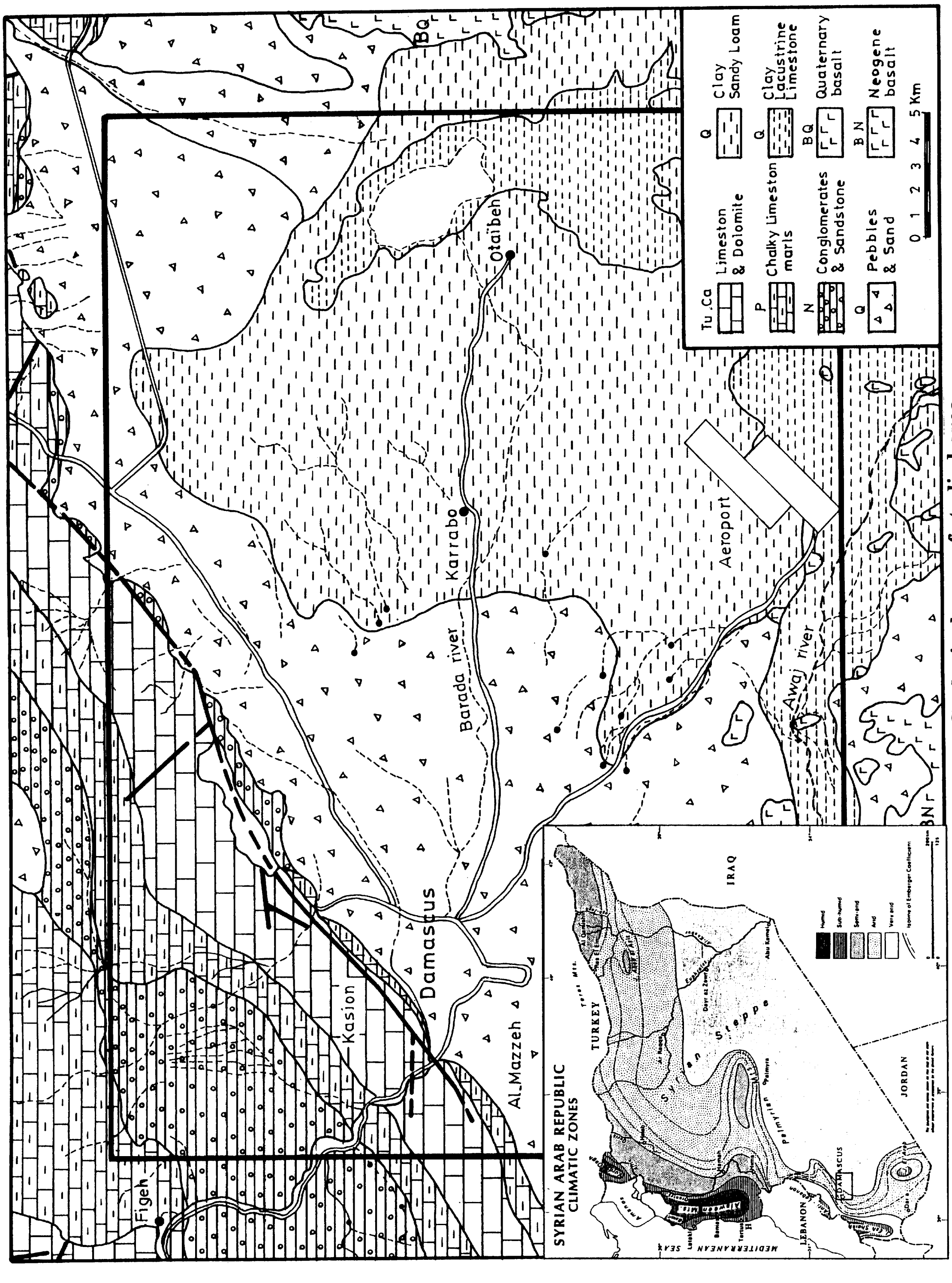

Fig. 1- Geological map of studied area

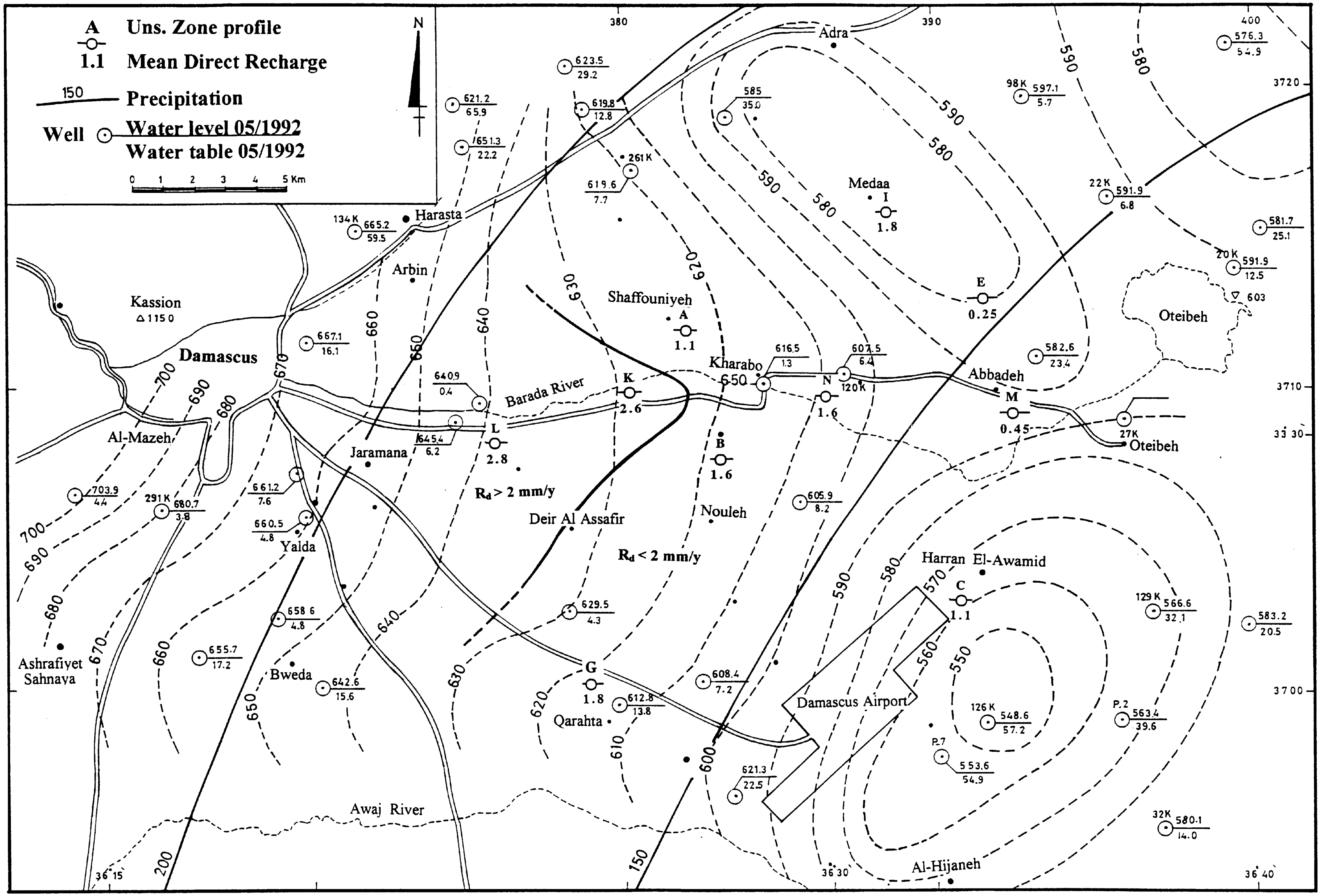

Fig. 2- Pesometric Map (Damascus Basin)

The transmisivity is relatively high near Damascus and it decreases progressively towards the east. The water flow is homogeneous in the aquifer but the velocity decreases when the clay content increases in sediments. This could be the reason of several spring's existence along north-south zone passing Kharabo area: i.e. Der Al-Assafir spring. In this zone the aquifer was invested by the "Fougara system".

It is mainly fed by infiltration of surface water. Towards the east of Oasis plane, the water of Barada and Awaj disappear slowly, but in flood periods the runoff reaches the middle part of the depression. The second source in feeding the aquifer is the groundwater flows.

In another hand, the pesometric seasonal variations show that rainfall shares directly or indirectly in feeding the aquifer.

4. The climate

The area is located in arid and semi arid zone of Mediterranean type which is generally characterized by irregular and variable precipitation distributed through 8 months in the year (Oct.-May), 20% of precipitation falls during Oct., April and May, whereas, 80% falls during the period from Nov. till March.

The mean annual precipitation is 221 mm/y in Al - Mazzeh, 167 mm/y in Kharabo and 136 mm/y at Damascus airport [5]. The meteoric line of 200 mm goes to the east of Al Mazzeh to NE-SW direction, while the line 150 mm goes to the west of airport and the east of Kharabo in the same direction (Fig.2). The intensity of rainfall value reaches more than 50 mm/h, separated by dry periods about 40 days in average with a maximum of 150 days.

The evaporation "piche" which is measured by "Lambrecht" method evaluated between 1326 mm and 2312 mm, the mean annual evaporation from the soil surface is 240 mm in Kharabo [6] calculated by (Penman, Planky-Cridle and Evanov method) is about 1554 mm/y, 1339 mm/y and 1305 mm/y respectively [7]. 80% of evaporation process happen between April and October, however, we have less evaporation rate in Jan.

The mean annual temperature is 17.5 °C in Al-Mazzeh, 16.5 °C at Airport and 15.8 °C in Kharabo. During hot months, these values reach 24.9 °C, 26.2 °C for July and August. However, during cold months it reaches 6.1 ºC for Jan. The absolute maximum temperature value is between 22 °C in winter and 44 °C in August, when the minimum temperature value is between –18.5 °C in Jan. On the regional scale, the temperature increases from the west and north west towards the east and southeast.

The relative humidity is 50% in Al- Mazzeh, 57% at airport and 60% in Kharabo. The maximum is 70-77% in Dec. and Jan., when the minimum is 34-48% in June. The average relative humidity is less than 30% in 200 days annually.

The isotopic contents of precipitation in Damascus city between 1989-1990 [8] ^{18}O values between –6.46 ‰ and –9.64 ‰, the mean weighted value is – 7.59 ‰, Deuterium content is between –35.5 ‰ and –71.1 ‰, the mean weighted value is – 45.1 ‰ and the tritium is between 5.5 and 13.6 TU, the mean weighted is 8.5 TU.

The local meteoric line calculated for 11 meteoric stations in Syria for the same period is given by this equation: δ δ

$$^{2}H = 8.26\ ^{18}O + 19.3$$

The altitude effect for all stations gives isotopic content, between –0.23 ‰ /100m for ^{18}O and –1.65 ‰/100 m for ^{2}H.

5. Field work

During Sept. 1996, profile (I) was drilled with a depth of 20.6 m in Damascus oasis. In addition to profile (H) with 2.5 m depth in Hamedieh region, south of Tartous City, in order to have a good correlation between the coastal area and Damascus oasis data. In June 1997, profile (N) was drilled with 4.75 m depth. In June- July 1998, profiles (A) and (B) were drilled with 5.85m and 5 m depth respectively. And in Oct. 1998, profiles (K), (E), (C) and (L) were drilled with 5.3 m, 5.55 m, 2.05 m and 1.55 m depth respectively.

A hand ogger was used with a vertical interval of 2-25 cm depth for stable isotopic enrichment peak and tritium determination. The lateral distribution of profiles is useful for spatial distribution study of direct infiltration rate in Damascus oasis and comparing this rate with that in the coastal area presented by profile (H). In other hand, profile (I) is a very useful tool for Tritium peak determination through unsaturated zone in the period of atmospheric nuclear tests during the sixties. Part of the soil samples was put in airtight containers in order to avoid evaporation and atmospheric air pollution, because they will be used for isotopic analyses in addition to chemical, granulomitry and mineralogical analyses.

6. Lab. work

The following labwork was done:

- Water extraction from soil samples under complete vacuum conditions.
- Granulometry, humidity and mineralogical measurements.
- Isotopic analyses (^{2}H, ^{3}H) of extracted water from soil samples.

6.1. Water soil extraction

The extraction of water from soil samples by distillation under complete vacuum condition is done [9] [10] [11] [12] [13] [14] [15] [16] [17] in isotopic geochemistry lab./Engineering high school in Sfax (Tunis), in order to do the tritium analyses in the water samples in the profile (I).

6.2. Granulometry, mineralogy and humidity measurement

Granulometry was performed for (I, B, A) profiles, because these profiles gives a good idea of sediment granulometry in Damascus oasis. Mineralogy also performed for (I) profile using X ray diffraction, in addition to humidity measurement that were done in the Geology dept. labs. / AECS.

6.3. Chemical analyses

Elution solutions of sediments were prepared for these analyses. This method is presented by adding a certain volume of distilled water (50 ml) to a certain amount of the soil (20 g), then shaking for 45 min., filtrating the mixture by filter papers after [1][11][12][14][16] [18].

The chemical balance of the elutriated analyses is given as follows:

$$Mw * C_R = Q * Cq \Longrightarrow C_R = (Q * Cq) / Mw$$

Where Q: the elution water quantity (50 ml)
Cq: the concentration of elution water
C_R: initial solution concentration in the soil
Mw: Water mass in the soil

Chloride, Nitrate, Ammonia analyses were performed in order to determine the Chloride balance in the soil, the direct infiltration rate and the spatial distribution, and study the Nitrate and Ammonia distribution in the profiles of the unsaturated zone to determine the pollution rate.

These analyses were done for all profiles in the AECS, Profile (I) in BGS lab. /UK to compare the results between the two labs.

6.3.1. Determination of Chloride balance and the direct recharge

The upper evaporation zone is not considered, whereas the lower part of the profile is studied because the concentration of Chloride is homogeneous and the infiltration process is under steady state conditions. Arranyossy, (1991) [1].

The chemical balance of Chloride as follows [1][19][20][21][22][23]:

$$Rd * C_R = P * Cp \Longrightarrow Rd = (P * Cp) / C_R$$

Where P : The annual average rainfall
Cp: The Chloride concentration in rainfall
Rd: The direct infiltration rate
C_R: The Chloride concentration in the infiltrated water.

6.4. Isotopic analyses ^3H, ^2H

Deuterium analyses of profile (I) were done in BGS lab. /UK using Zinc reduction method for part of wet soil (Darling method1989)[24] for evaporation rate determination.

A few selected samples of profile (I) were performed for Tritium measurements, in order to determine the Tritium enrichment peak belong to the beginning of sixties for effective infiltration velocity estimation.

6.4.1. Isotopic profiles construction

Three phenomena are controlling the isotopic content of unsaturated zone by evaporation [25] [26] [27] [28]:

- The isotopic enrichment is related to temperature, relative air humidity, isotopic content of water vapor, in the atmosphere and the groundwater feeding the evaporation system.
- Water vapor diffusion in the upper part of profile where the zone of gas transfer is dominant, the heavy isotopes are concentrated in the lower part of the profile.
- Heavy isotopes diffusion occur in the lower part of profile where the zone of liquid transfer is dominant, and it increases in the upper part of profile.

These three phenomena are used to construct the evaporation profiles [29] [30] [31] [32] Arranyossy, 1991 [33] [34], determined in Bilma / Niger the effect of different conditions on the calibration of the experimental isotopic profile on calculation of the evaporation rate using mathematical modeling and in the lower part where the zone of liquid phase is dominant, it was given respectively the importance of temperature, isotopic content of the enrichment peak, the isotopic content of reservoir, tortuosity and the bulk density and volumetric water content. The upper part of profile where the zone of gas transfers is dominant, it was given respectively the importance for the isotopic enrichment of the peak, the relative air humidity, the air temperature and the porosity.

6.4.2. Estimation of evaporation rate

Barnes and Allison, 1983 suggested [30] [31] [32] a mathematical model of isotope content variations and estimate the evaporation rate through the unsaturated zone where it is divided into two parts:

- Zone of liquid transfer phase is dominant:
Presented by this equation:

$$\delta_i - \delta_i^{res} = \left(\delta_i^{ef} - \delta_i^{res}\right)\exp\ \left[-f(z)/\bar{z}_i\right]$$

δWhere: δ_i : isotopic content

δ_i^{res} : Isotopic content of groundwater (reservoir)

δ_i^{ef} : Isotopic contents of the evaporation front (the peak)

Z : The depth

$f(z)$: A function of depthδ

- Zone of vapor transfer phase is dominant:

Δ

$$\delta_i = \left(\delta_i^*\right)^{-1}\left\{\delta_i^a + \left(1-\alpha_i^*\right) + \left[\eta_i\left(1-\delta_i^{res}\right) + \left(\delta_i^{res} - \delta_i^a\right)\right]\ \left[z/\left(z+h_a\bar{z}\right)\right]\ \right\}$$

Where: α_i^* : The equilibrium fractionation factor between vapor and liquid (Parametric constant dependent on Temperature).

α_i^a: The stable isotope content of the water vapor in the free atmosphere above the profile.

η_i : Parameter, which accounts for the kinetic effect occurring during the diffusion of gaseous molecules through the air columns.

h_a: The average relative humidity of the atmosphere

$\bar{z}$: The “penetration depth”

7. The studied profiles

7.1. Profile I (Table 1)

7.1.1. The Granulometry, mineralogy and humidity measurement

Fig. 3 Presents around 90% of the profile is a granular clay and fine loam, the remaining part about 10% is big loam and sand which forms this lenses or layers of 40% sand.

The granulometry profile shows the alternation of sedimentation periods between high rate of sand and high rate of clay and fine loam.

Fig. 4 of mineralogy is divided into the upper part, from surface till 10 m depth and the lower part from 10-21.6 m depth. The lower part is consisted of 90% of carbonatic minerals (Calcite, Dolomite) whereas the Quartz forms around 5% in average. The upper is consisted of 60% of Carbonates, 35% of quartz which may be reach more than 90% at some levels (at 4.5 m depth). The clay is around 5% in average.

Table 1. Chemical and isotopic data (profile I)

n°	Depth (from to cm)	Depth (cm)	H% UK	Cl (mg/l) UK	NO3-N (mg/l) UK	2H%o UK	2H%o Calcu.	T (TU) IAEA	H% Syr.	Cl mg/l Syr.
I1	0-2	1	1.97	503.07	194.94	-94.00	-93.40		2.63	5912.17
I2	2-4	3	2.27	261.88	595.44	-86.00	-85.19		3.53	2031.44
I3	4-6	5	2.81	143.37	336.81	-63.00	-78.14		3.93	1535.62
I4	6-8	7	3.59	59.23	31.46	-59.00	-72.07		4.61	1062.69
I5	8-10	9	4.56	205.32	38.59	-53.00	-66.80		5.49	1138.07
I6	10-14	12	5.58	589.11	131.36	-36.00	-60.06		6.68	2327.69
I7	14-18	16	8.30	449.13	104.69	-37.00	-52.76		8.50	1461.76
I8	24-30	27	10.71	656.34	147.92	-30.00	-39.89	14.92	10.76	1867.38
I9	36-44	40	12.40	629.21	160.06	-28.00	-28.89		12.23	1654.54
I10	55-65	60	13.94	682.09	180.39	-32.00	-37.31	10.23	13.42	1317.36
I11	75-85	80	15.56	742.38	159.41	-41.00	-40.79		14.40	995.97
I12	95-105	100	15.32	581.14	103.03	-36.00	-43.94	42.02	14.24	1944.52
I13	115-125	120	13.71	660.40	96.59	-45.00	-46.93		12.65	2295.57
I14	135-145	140	12.81	563.31	73.19	-51.00	-49.69	5.04	12.54	1239.95
I15	155-165	160	13.96	545.85	55.26	-56.00	-52.00		13.08	1009.63
I16	195-205	200	20.91	1425.72	98.60	-58.00	-55.70	6.71	18.17	1211.34
I17	220-230	225	28.73	1462.71	78.98	-55.00	-56.22		24.40	1018.44
I18	245-255	250	23.30	985.80	52.63	-68.00	-58.38		25.45	836.94
I19	270-280	275	19.34	752.29	56.20	-68.00	-58.93		17.71	914.06
I20	295-305	300	18.67	602.34	55.21	-54.00	-60.93	6.37	17.32	1475.75
I21	320-330	325	16.67	554.94	60.86	-55.00	-61.41		15.05	943.52
I22	345-355	350	12.89	330.77	38.85	-51.00	-63.33		12.03	1150.87
I23	370-380	375	9.68	262.71	29.80	-67.00	-63.81		9.61	1219.04
I24	395-405	400	17.66	659.06	59.91	-63.00	-64.97	3.77	17.23	679.92
I25	420-430	425	25.24	1013.81	80.98	-70.00	-65.17		18.14	555.79
I26	445-455	450	31.99	1602.99	109.01	-67.00	-65.77		26.49	332.35
I27	470-480	475	21.67	1028.45	72.10	-66.00	-65.96		19.29	449.04
I28	495-505	500	17.74	839.27	67.39	-60.00	-66.71	3.74	16.55	467.61
I29	535-545	540	14.07	549.15	31.64	-48.00			12.87	601.32
I30	575-585	580	13.79	558.93	23.62	-49.00			12.75	501.18
I31	615-625	620	15.19	516.06	16.16	-56.00			13.80	977.54
I32	655-665	660	24.61	1548.02	38.33	-53.00		1.73	20.25	711.75
I33	695-705	700	24.21	1442.29	35.00	-59.00			21.25	711.67
I34	735-745	740	24.19	1250.57	36.44	-52.00			20.59	758.62
I35	775-785	780	14.95	682.41	22.98	-46.00			13.77	1046.70
I36	815-825	820	13.43	689.97	17.89	-49.00		4.35	12.42	1086.15
I37	855-865	860	10.51	448.42	8.77	-43.00			9.88	1171.36
I38	895-905	900	15.63	717.87	10.49	-54.00			14.26	707.01
I39	935-945	940	14.91	645.13	9.18	-42.00			13.82	1032.63
I40	975-985	980	21.79	1019.55	9.55	-50.00		10.30	19.59	761.10
I41	1015-1025	1020	18.17	1023.18	9.91	-38.00			15.84	1295.39
I42	1055-1065	1060	20.14	1024.62	10.44	-44.00			16.95	921.53
I43	1095-1105	1100	20.91	1011.33	13.72	-47.00			17.91	804.75
I44	1135-1145	1140	18.13	641.00	8.66	-44.00			16.30	784.05

Table I. (cont.)

I45	1175-1185	1180	21.69	539.01	6.81	-41.00			18.11	666.48
I46	1215-1225	1220	31.04	808.07	12.22	-42.00			24.48	435.05
I47	1255-1265	1260	31.16	747.49	12.25	-39.00			24.53	408.11
I48	1295-1305	1300	27.51	564.14	9.56	-39.00			27.46	312.86
I49	1335-1345	1340	25.01	371.11	10.43	-39.00			19.04	380.36
I50	1375-1425	1380	18.42			-46.00			13.62	589.06
I51	1415-1425	1420	19.77	206.72	10.34	-46.00			16.78	456.97
I52	1455-1465	1460	18.53	183.72	11.25	-51.00			15.56	460.86
I53	1495-1505	1500	15.33	177.16	8.11	-44.00			13.26	621.12
I54	1535-1545	1540	18.24	232.06	6.20	-47.00			15.72	501.34
I55	1575-1585	1580	18.88	210.72	8.83	-34.00			16.28	484.09
I56	1615-1625	1620	22.37		6.93	-28.00			17.89	440.53
I57	1655-1665	1660	24.51	224.96	5.88	-32.00			19.71	432.27
I58	1695-1705	1700	29.01	387.81	6.63	-44.00			28.97	318.61
I59	1735-1745	1740	31.14	409.42	1.57	-43.00			22.57	443.55
I60	1775-1785	1780	36.52	445.83	0.20	-39.00			26.84	439.12
I61	1815-1825	1820	34.29	462.92		-46.00			24.75	542.18
I62	1855-1865	1860	19.09	210.62	3.81	-30.00			20.63	650.46
I63	1895-1905	1900	17.20	218.80	6.04	-33.00			15.70	524.59
I64	1935-1945	1940	26.48	263.60	0.06	-45.00			21.03	428.77
I65	1975-1985	1980	43.64	436.06	0.70	-40.00			30.27	330.72
I66	2015-2025	2020	43.15	376.63	1.84	-41.00			31.40	221.59
I67	2055-2065	2060	22.92	133.74	0.08	-46.00			19.63	672.75

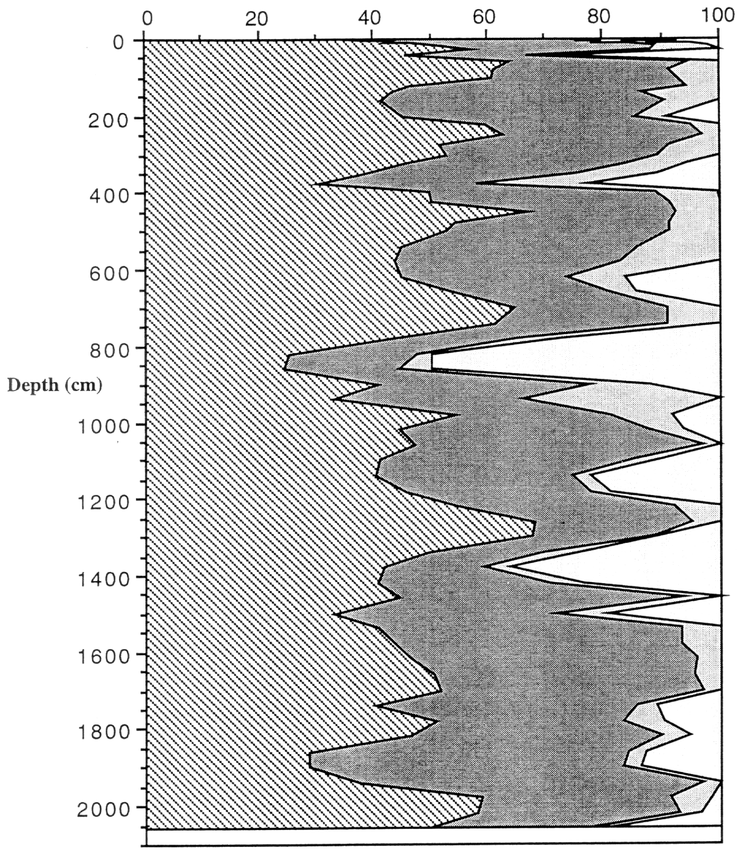

Fig. 3- Granulomitry : Profile I.

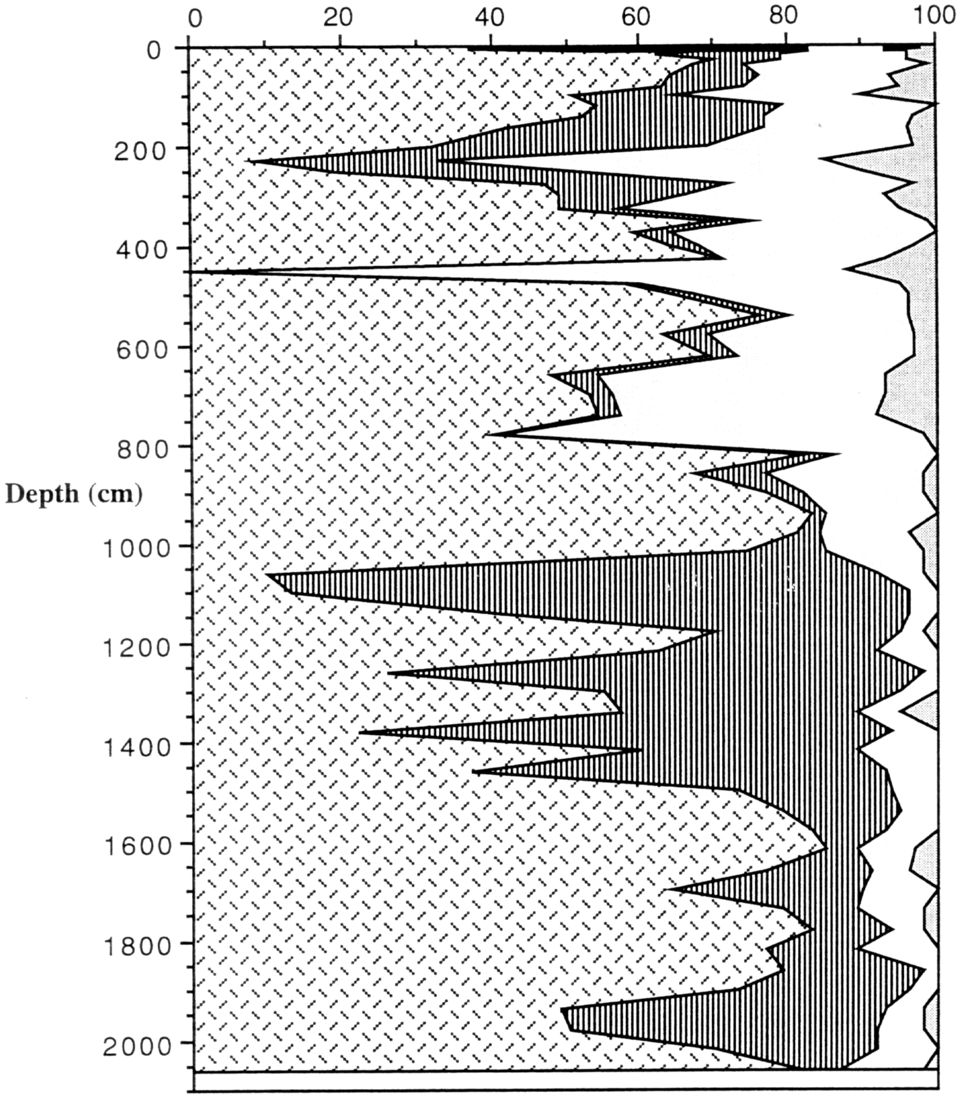

Fig. 4- Minerale analysis "XR" Profile I.

The mineralogy of lower part reflect the sedimentation conditions and erosion under relatively wet climate conditions, whereas the chemical erosion with high fine sediments and carbonatic minerals rate and the upper part characterized by relatively dry climate conditions characterized with high sand and quartz where the aeolin is dominant.

The weighted humidity profile shows the humidity changes with depth. From the surface it is 2% and increases till 15% at 1 m depth and at 2.5 m depth it reaches 25%. Generally, it is increased till 30% at 20 m depth. There is an alternation of low and high humidity ratio between 10-15% and 25-30% and it is paralleled with granulometry profile. It is noticed that the humidity increases with clay ratio increasing, and decreases with sand ratio increasing.

Humidity measurements were done in the AECS, fig.5 compared with these in BGS lab. /UK. Fig.6. A good correlation was found between the two profiles.

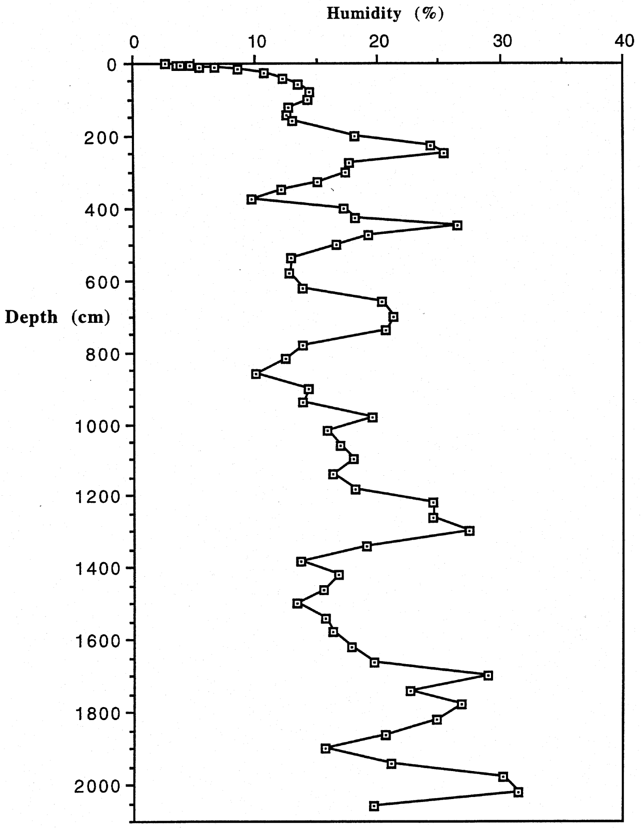

Fig. 5- Relationship between humidity and depth (Profile I), Syr. Lab.

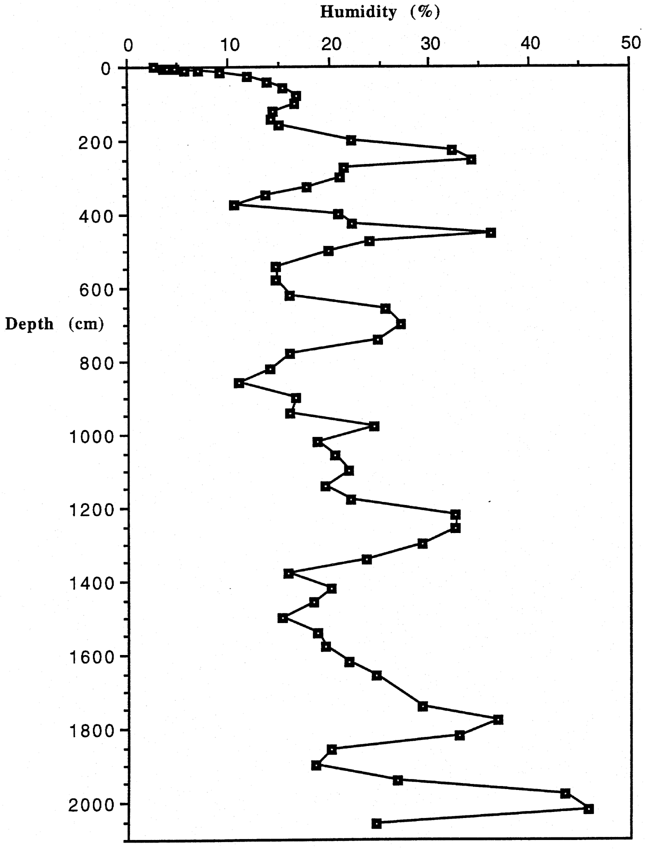

Fig. 6- Relationship between humidity and depth (Profile I), UK lab.

7.1.2. Estimation the direct infiltration rate

A comparison between the chloride analyses of the profile in AECS, Fig. 7, with these were done in BGS lab/ UK fig.8, and a good correlation was found. All these data will be used for estimation the direct infiltration rate and make a comparison between the two labs.

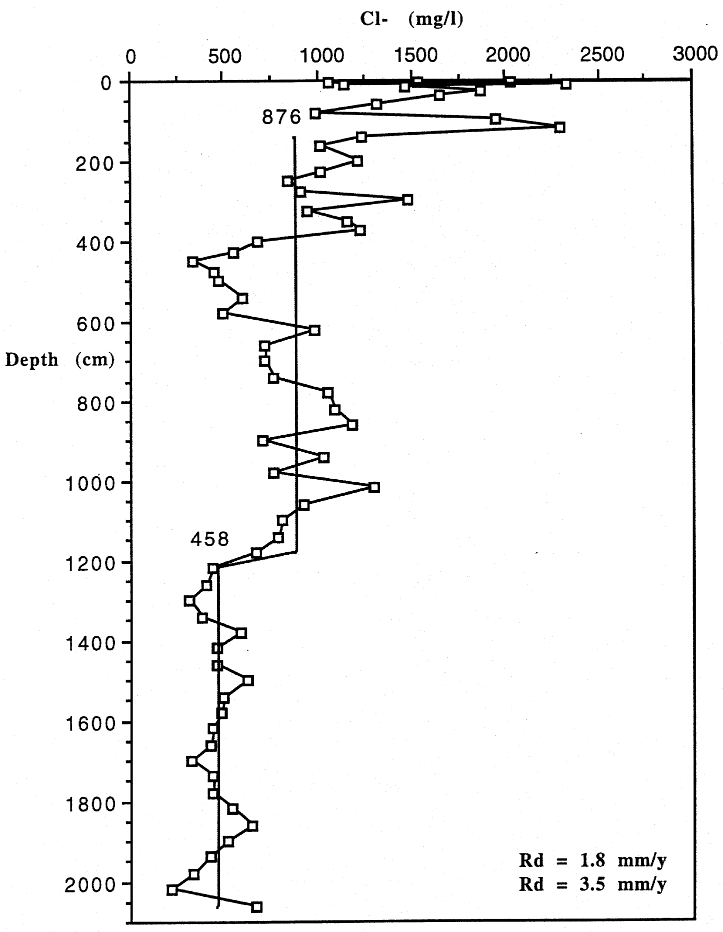

Fig. 7- Relationship between chloride and depth (Profile I) Syr. lab.

The upper part of the profile (Evaporation zone) is characterized by high Chloride concentration because of evaporation process Fig.7. Fig.8, shows the Chloride concentration in the upper part changes between 300 mg/l and 1500 mg/l, that would indicate the alternation between wet period where the direct infiltration increases and relatively dry period where the Chloride ratio is increases in the soil with decrease in direct infiltration.

Generally, we differentiate between surface part of 2–12 m depth (Fig.7) till 14 m depth (Fig.8), the Chloride concentration is 876 mg/l and 838 mg/l respectively. And the deep part of 12–14 m depth till 20 m depth where the Chloride concentration is 458 mg/l and 269 mg/l respectively.

The estimated vertical recharge quantity or the direct recharge rate in two labs. is presented in the following table:

Pro.I	P mm	Cp mg/l	Cr1 mg/l	Rd1 mm/y	Cr2 mg/l	Rd2 mm/y
Syr. Lab.	220	7.25	876	1.8	458	3.5
BGS lab.	220	7.25	838	1.9	269	5.9

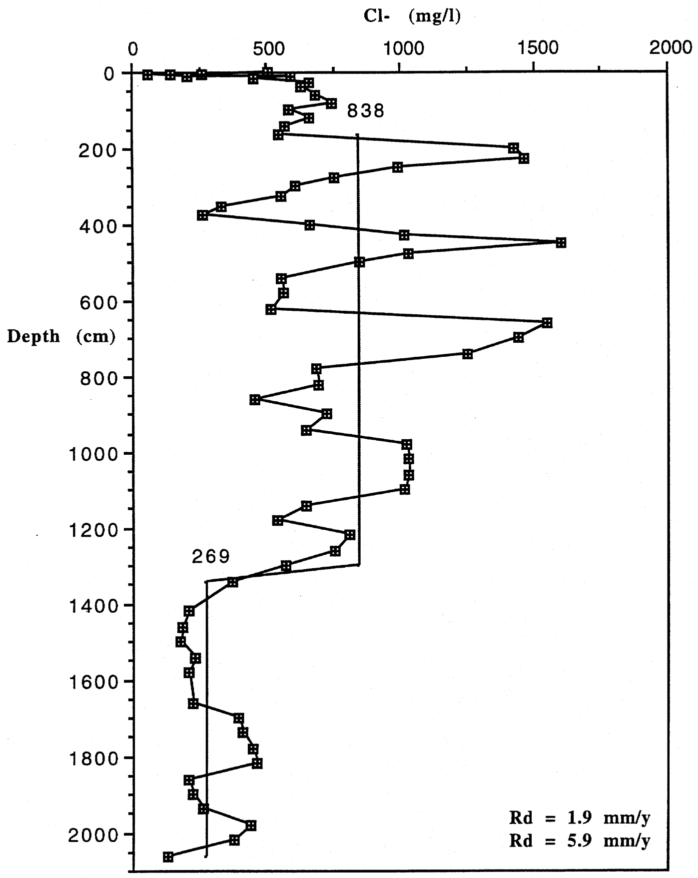

Fig. 8- Relationship between Chloride and depth (Profile I), UK lab.

The upper part of the profile has a direct vertical recharge of Rd1 = 1.8 mm/y that is close to the other values in the other profiles. The lower part of profile of 12-14 m till 21 m depth has a direct recharge twice or more than twice of the recent value, Rd2 = 3.5 mm/y, Rd2 = 5.9 mm/y respectively. It is considered that this value is affected by more wet climatic conditions, where the mean rainfall is around 423 mm/y for direct recharge of 3.5 mm/y and 682 m/y for direct recharge of 5.9 mm/y.

If the effective direct infiltration velocity value that is calculated by tritium of around 27.8 mm/y is taken into consideration, the time for 12 m depth (Fig.7) is 432 years where the wet period is terminated. Fig.8, presented the end of wet period at 14 m depth started about 504 years till more than 760 years ago.

7.1.3. Deuterium profile

Fig.9 presented a typical evaporation of deuterium profile from the surface till 5 m depth. The isotopic enrichment of deuterium increases with depth because the profile is non-isothermally homogeneous. The lithological changes from pure clay to pure sand are the reason of non-vertical homogeneous of profile. Allison & Barnes 1983 model is applied on the evaporation part of profile (Fig.11). The upper part of the profile from surface till 40 cm depth where the isotopic enrichment peak is located, that presenting the part of vapor transport is dominant. The lower part from 40 cm-5 m depth presenting the part of liquid transfer is dominant. The evaporation rate in the upper part is E (vap.z) = 5 mm/y, and in the lower part is E (Liq.z)= 6 mm/y.

7.1.4. Tritium profile

Fig.10 of Tritium profile shows a peak at 1 m depth where the tritium value is 42.02 TU that could be the cause of high input tritium concentration into the unsaturated zone that is occurred by atmospheric nuclear tests during the sixties (1963). The effective infiltration velocity is computed depending on the transit time of 36 y:

$$\text{Veff.} = (1000/36) = 27.8 \text{ mm/y} = 8.8*10^{-10} \text{ m/s}$$

This indicates the low direct infiltration rate, due to clay and fine loam soil.

The annual infiltrated water value is determined of about 1.8 mm considering the infiltration water volume is equal to effective porosity, the mean effective porosity is calculated as follows:

$$n = (1.8/27.8) = 6.5*10^{-2}$$

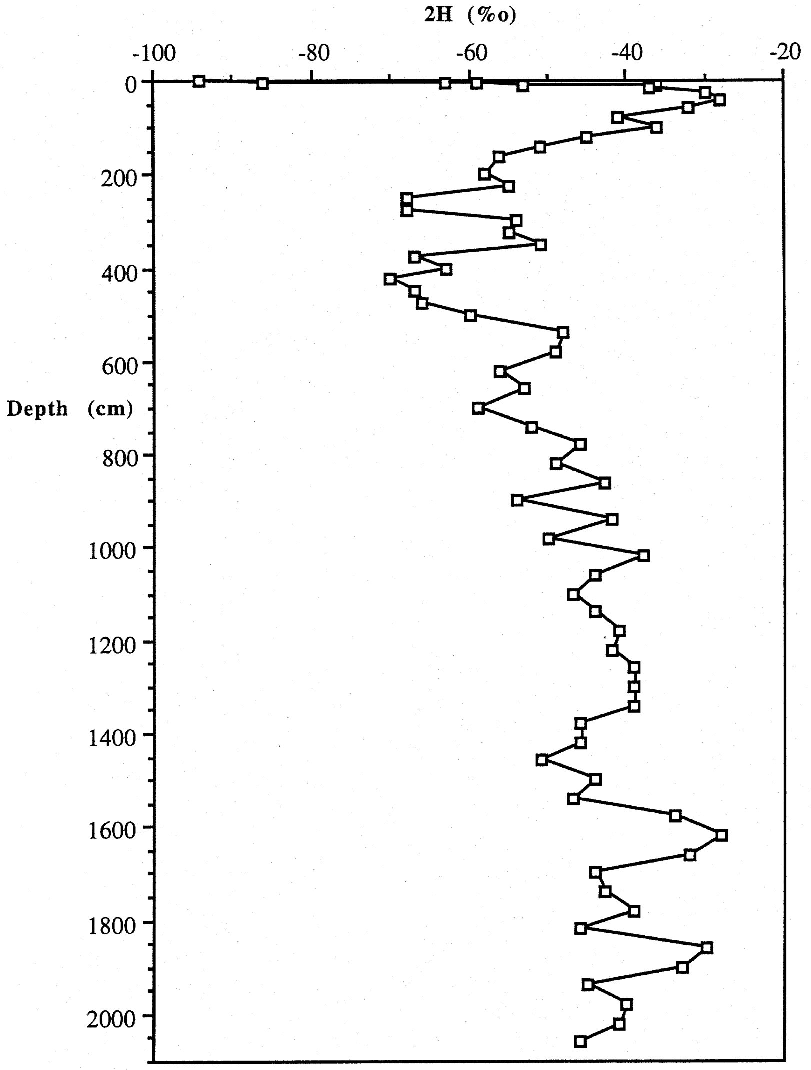

Fig. 9- Relationship between deuterium and depth (Profile I), UK lab.

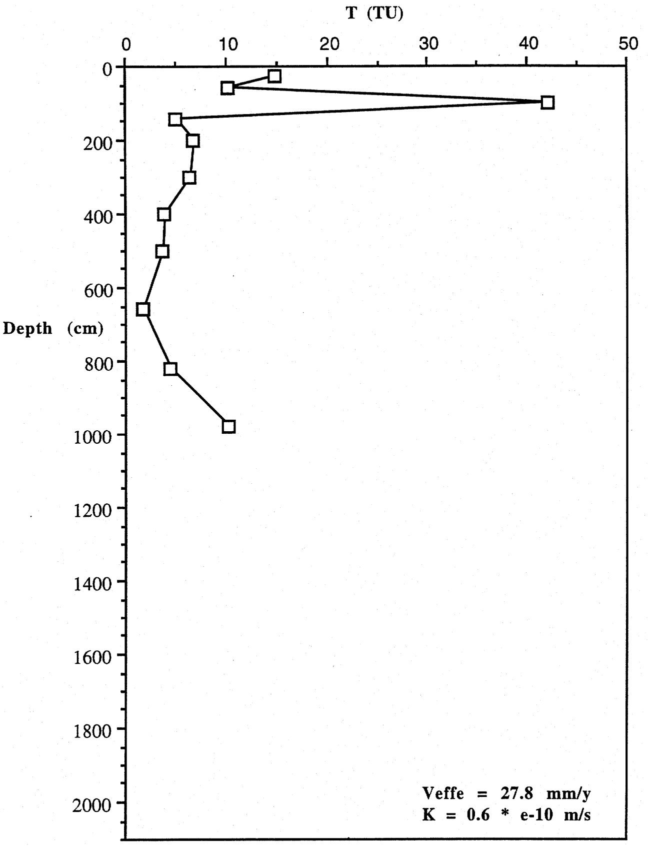

Fig. 10- Relationship between tritium and depth (Profile I), IAEA lab.

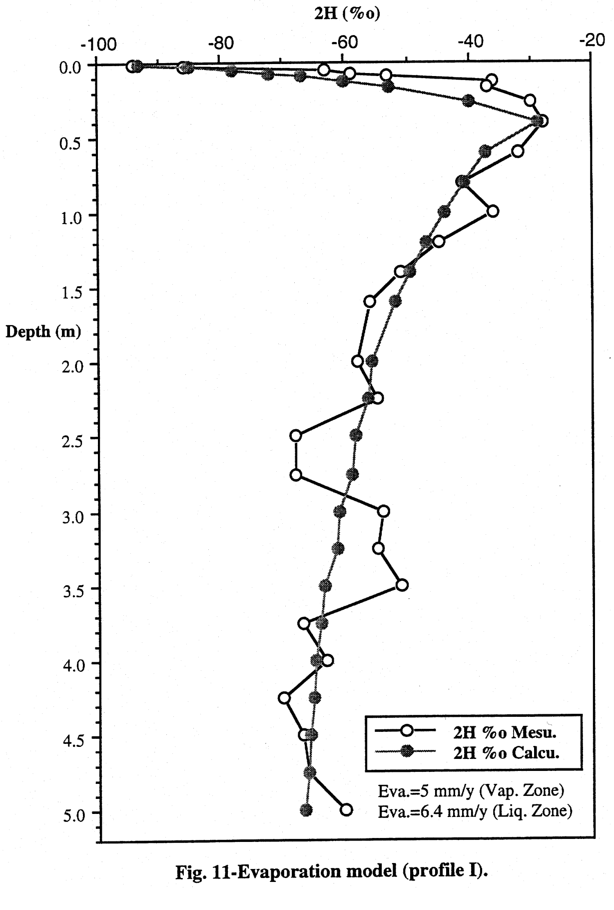

Fig. 11-Evaporation model (profile I).

The applied Darcy's law is $V_{Dar^{\cdot}} = K\ i$ and the hydraulic gradient in the vertical infiltration is i = 1, so the Darcy velocity is equal to the permeability parameter K:

$$V_{eff} = (V_{Dar.} /n) = K/n$$

$$K = V_{eff.} * n = 8.8*10^{-10} * 6.5*10^{-2}$$

$$K = 0.6 * 10^{-10}\ m/s$$

It is obvious that the porosity parameter K is very low, so the soil is semi-permeable.

7.1.5. Nitrate profile

Fig.12 indicates the Nitrate changes along the profile, the pollution peak is located in the surface part of profile where the concentration is more than 300 mg/l, and decreases at 1.75 m depth till 50 mg/l. At 2 and 4.5 m depth there is two peaks, the concentration value is more than 100 mg/l, and decreases till less than 50 mg/l at 5 m depth and 10 mg/l at 8.5 m depth.

The Nitrate pollution is due to the human activities and agricultural purposes that is located in the surface layers till 5 m depth. There is a great danger of infiltration the high Nitrate concentration to the shallow aquifer (less than 5m depth). However, if the aquifer is deep the unsaturated zone plays a protecting zone from pollution (more than 5m depth).

7.2. Profile N (Table 2)

This profile is located near the "irrigation research center / Nashabieh", to the east of Kharabo. This profile was drilled in June 1997 in coordination with Mr. I.Sakabi (Representative of Saudi Arab Kingdom in the project) during his scientific visit to Damascus.

7.2.1. Granulometry

Fig.13 shows the granulometry of profile, more than 80% of profile consisted of sediment with granular size clay and fine loam. About 20% of sand and big loam where the sand ratio that is in a lental or thin layers with a thickness about 50 cm, is about 50% at 1.25 m depth. The sand ratio is related to the sedimentation periods and the dry climatic conditions.

7.2.2. Humidity

Fig.15 shows about 2% of humidity is started from surface and increases rapidly till 14% at 50 cm and 22% at 4.75 m depth. However, there is decreasing in the humidity at 65 cm, 125 cm and 325 cm depth caused by a high sand ratio.

7.2.3. Chloride profile

The Chloride peak that due to the evaporation process (Fig.16) is located in the surface of profile where the Chloride concentration is more than 15000 mg/l and decreases to 1000 mg/l at 75 cm depth. Then it varies between 150–1800 mg/l, and it is in average 1000 mg/l that is used for direct recharge rate estimation through the unsaturated zone. As the mean rainfall in

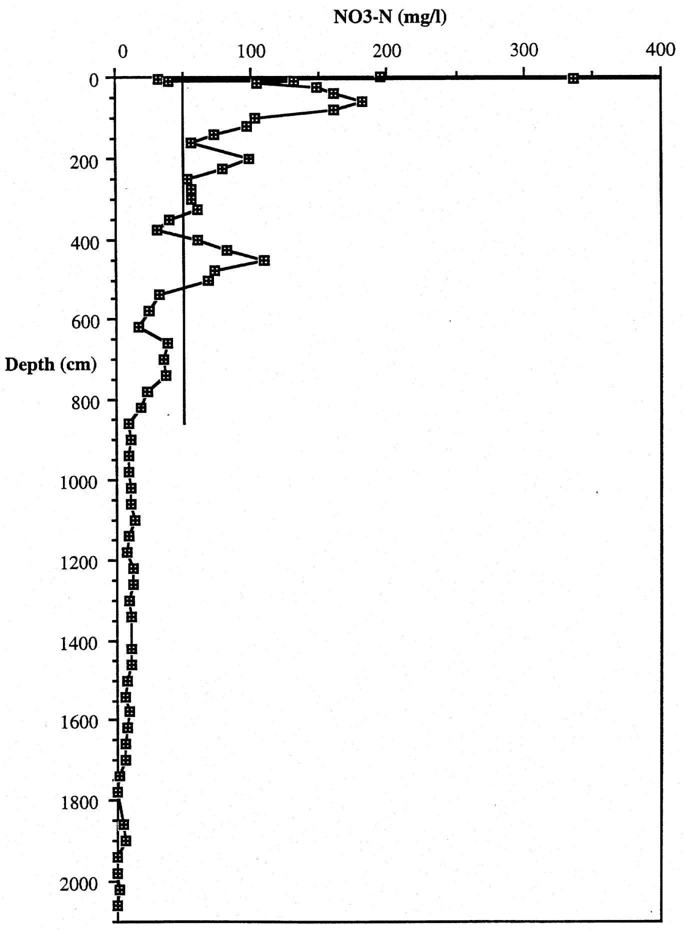

Fig. 12-Relationship between NO3-N contents and depth, (profile I), UK lab.

Damascus oasis is 220 mm/y, and the mean Chloride concentration for the years 1990, 91 and 92 is 7.25 mg/l:

$$Rd = (220 * 7.25)/ 1000 = 1.6 \text{ mm/y}$$

The mean direct infiltration through the evaporation zone that could reach the aquifer is 1.6 mm/y.

7.3. **Profile A** (Table 3)

It is located to the east of Shoufanieh village and has a depth of 585 cm.

7.3.1. Granulometry

Fig.14 presents two parts of profile, the upper part from surface to 2.75 m depth where the clay and fine loam ratio is around 65%, the sand and big loam ratio is 35%, and the lower part from 2.75 m to 5.75 m depth where the mean clay and fine loam ratio is 90%, the sand and big loam ratio is 10%. The sand that has a layer or lental shape reflects the sedimentation conditions and relatively dry climate, is alternated with clayey layers that indicate wet climate.

It is observed the good correlation between profile A and N because they are located on the same axe of the oasis, to the east and west of Kharabo center.

Table 2- Chemical data (profile N).

n°	Depth (fromto cm)	Depth (cm)	H %	Cl (mg/l)
N1	0-2	1.00	2.27	9383.26
N2	2-4	3.00	3.59	15821.73
N3	4-6	5.00	4.52	12566.37
N4	6-8	7.00	6.74	4582.34
N5	8-10	9.00	6.44	3417.70
N6	10-20	15.00	10.88	1500.92
N7	20-35	27.50	12.98	1941.83
N8	40-50	45.00	13.60	1853.31
N9	50-70	60.00	9.54	2716.46
N10	70-80	75.00	14.74	1059.70
N11	80-90	85.00	14.72	940.56
N12	90-100	95.00	14.47	932.27
N13	110-115	112.50	11.18	1238.37
N14	115-130	122.50	8.33	1576.83
N15	130-150	140.00	14.72	144.70
N16	150-165	157.50	16.44	1252.43
N17	165-180	172.50	17.15	1117.78
N18	190-200	195.00	17.27	883.90
N19	210-220	215.00	17.94	2295.43
N20	230-240	235.00	16.48	1507.89
N21	250-260	255.00	16.59	556.36
N22	274-280	277.00	18.18	546.75
N23	290-300	295.00	19.94	640.92
N24	310-320	315.00	16.06	839.98
N25	330-340	335.00	14.02	1088.80
N26	350-360	355.00	17.50	1014.29
N27	370-390	380.00	20.40	1026.72
N28	410-430	420.00	21.89	535.18
N29	450-475	462.50	21.41	1011.44

7.3.2. Humidity

Fig.17 indicates the first sample at 25 cm depth has humidity about 10% that is increasing at 75 cm depth to 20% then 23% at 5.25 m depth. At 2.5 m there is increases to 30% due to high clay ratio and decreases to 13% at 4 m due to high sand ratio that could shows generally an linear relation between the clay ratio and the relative humidity of soil.

7.3.3. Chloride profile

At 25 cm depth the evaporated Chloride peak has a value more than 3000 mg/l, then it decreases to 1500 mg/l at 75 cm, and varies between 1800–1000 mg/l at 0.75 m and 585m depth respectively. The low Chloride concentration in the profile is due to high humidity ratio in the clay layers. However, the high Chloride concentration is due to low humidity ratio in

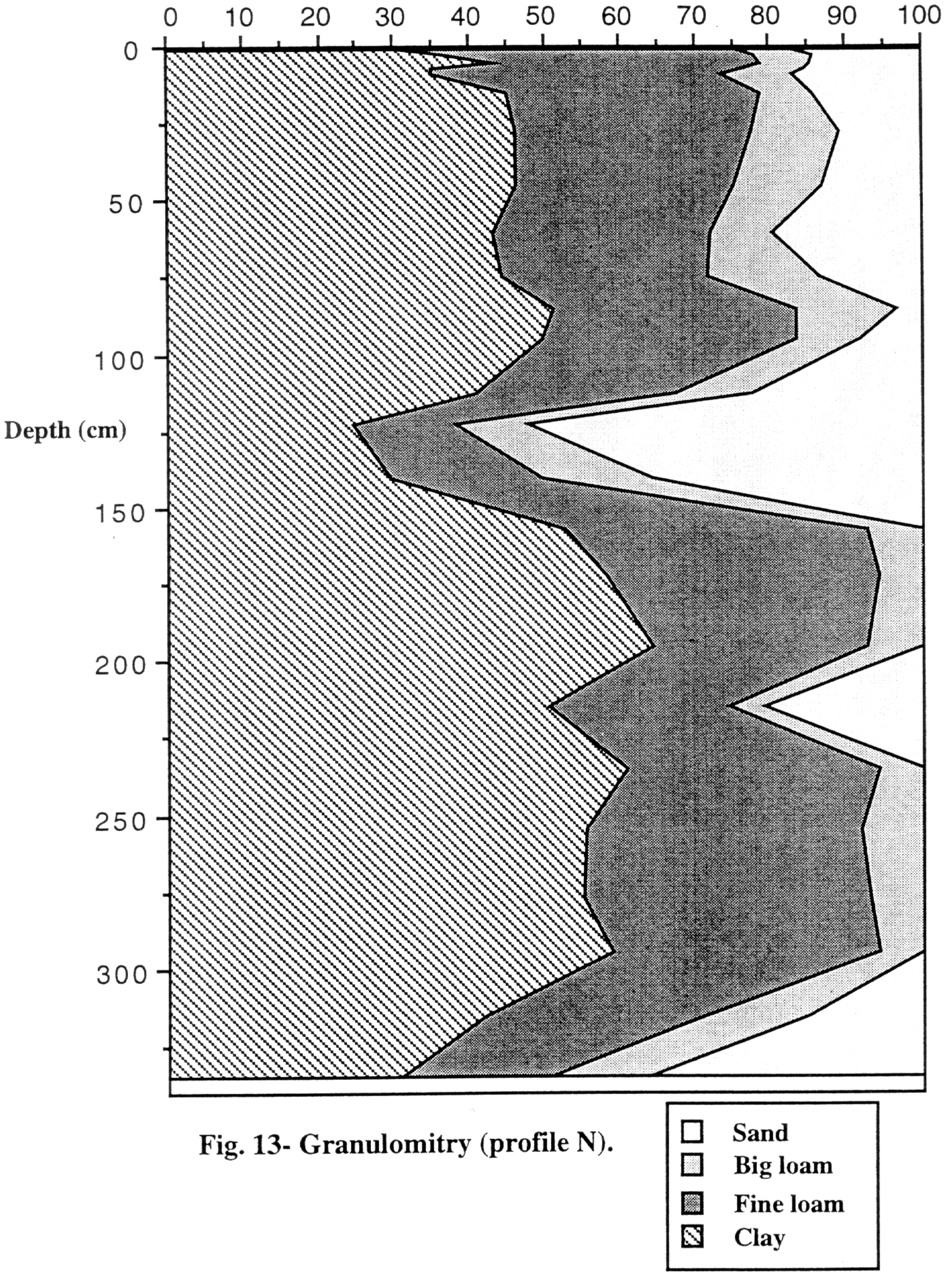

Fig. 13- Granulomitry (profile N).

the sandy layers. Considering the mean value of Chloride, We obtained the mean direct infiltration rate is about 1.1 mm/y along the profile.

7.4. Profile B (Table 4)

It is located to the south of Kharabo, with 5 m depth with every 25 cm interval. It is drilled in July 1998.

7.4.1. Humidity

The humidity increases (Fig.19) from 7% in the surface to 20% at 2.5 m depth then it decreases to 10% at 3 m, and increases to 30% at 4.5 m depth. The humidity profile reflects the sediment structure and the granulometry. More clay ratio causes high humidity ratio and less humidity is due to high sand ratio.

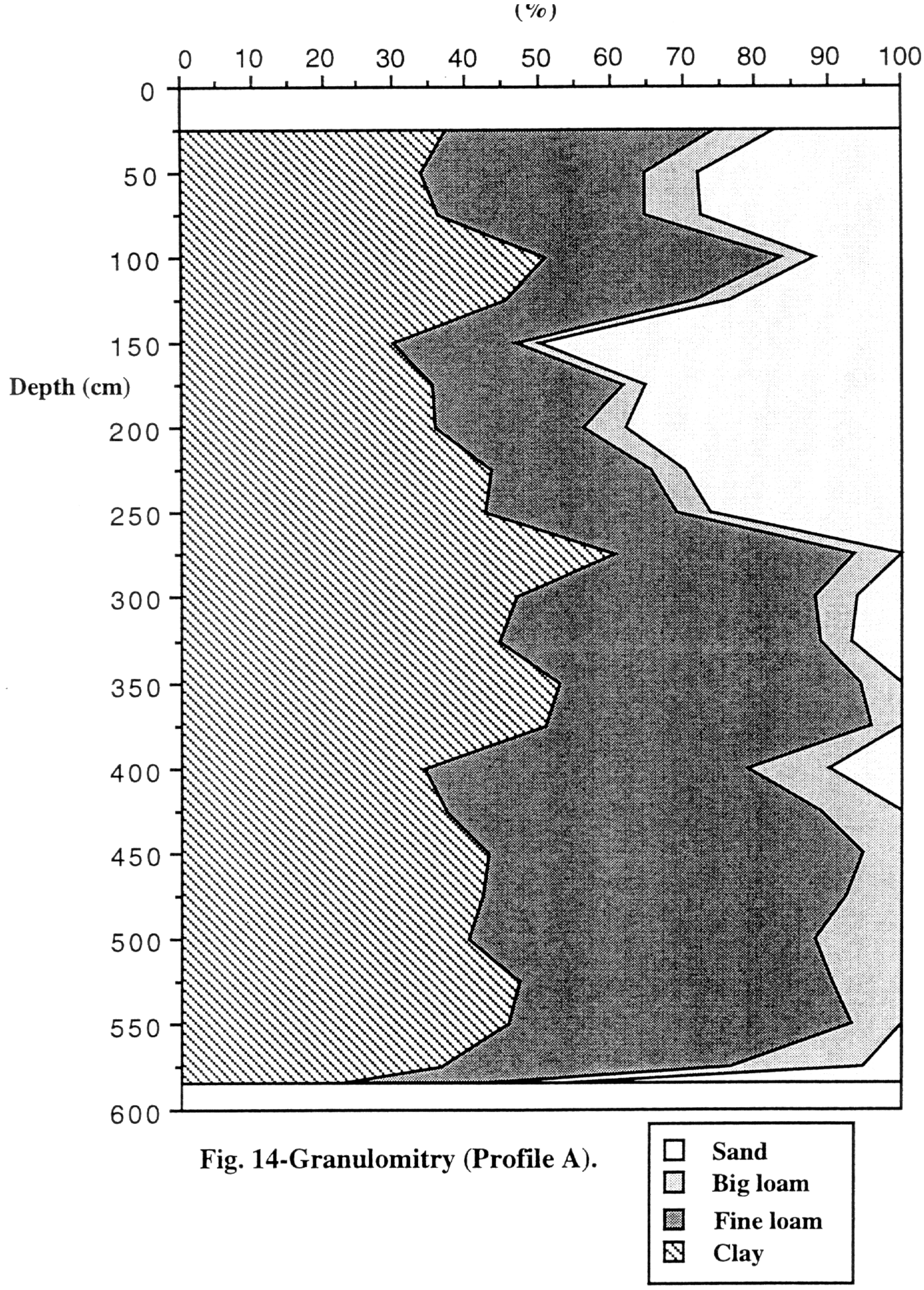

Fig. 14-Granulomitry (Profile A).

7.4.2. Chloride profile: Fig.20

Because of evaporation process the Chloride concentration increases in the surface to more than 7000 mg/l then it decreases to 1000 mg/l at 1 m depth, and reaches 950 mg/l at 1-5 m depth. The mean value is 988 mg/l gives a vertical direct recharge value of 1.6 mm/y that is close to this calculated in profile N.

7.5. Profile E (Table 5)

This profile was drilled in Oct.1998 with depth of 5.5 m and 25 cm step intervals, it is located in the eastern part of the oasis, to the west of dry Oteibeh lake. The sediments are fine and black clay change to become orange sand in some places.

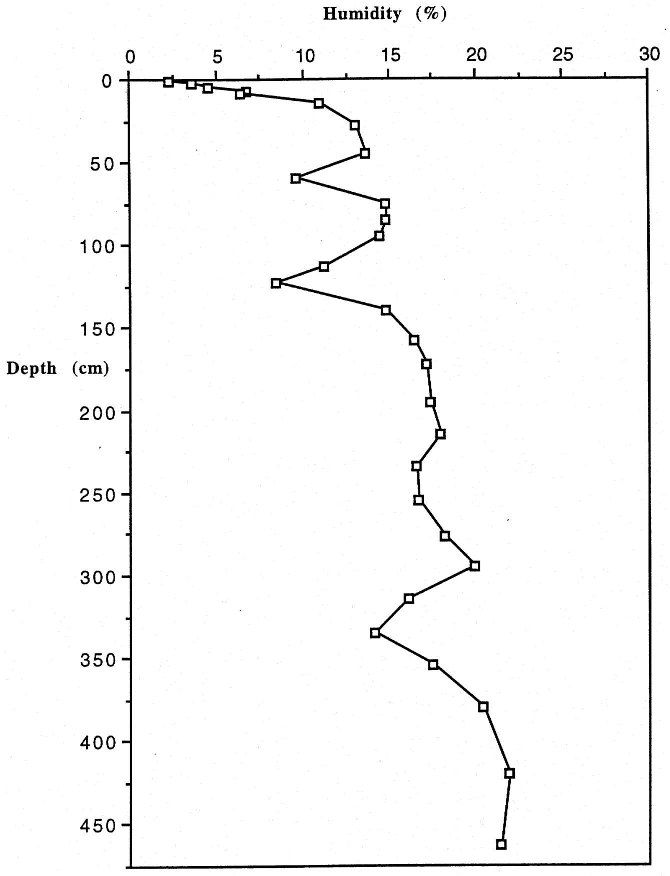

Fig. 15- Relationship between depth and humidity (Profile N).

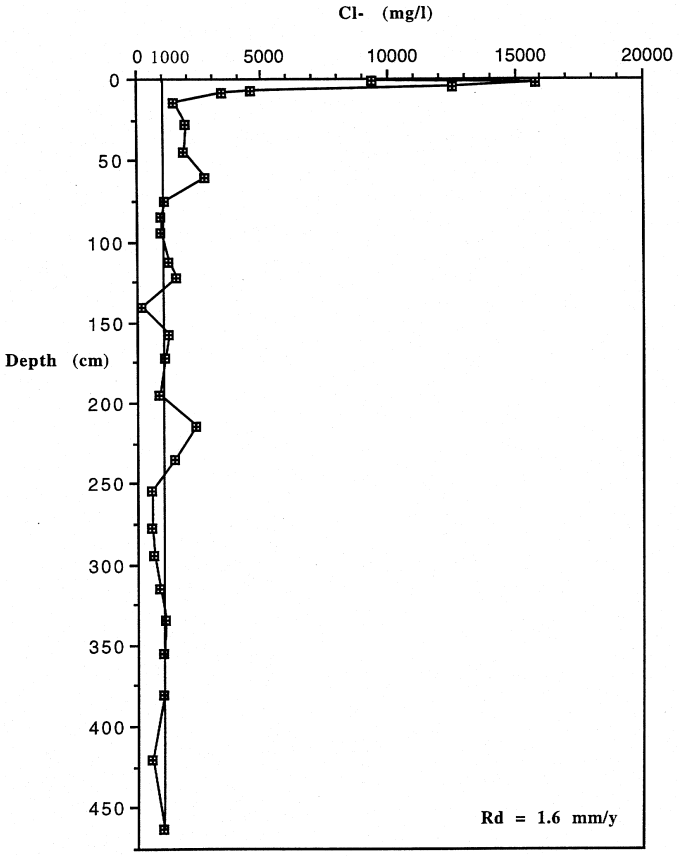

Fig.16- Relationship between chloride and Depth (Profile N).

7.5.1. Humidity: Fig.21

At surface the humidity has a value of 4%, then it increases to 22% at 2,25 m depth and decreasing to 9% at 2.75 m because of sand layers with 75 cm thickness. Then it reaches 24% at 3 m depth. At 5.5 m it decreases to 20%.

7.5.2. Chloride profile

At the surface the Chloride concentration is 33000 mg/l, and decreases to 10000 mg/l at 75 cm depth. At 5.5 m depth, it reaches 3000 mg/l. The mean Chloride concentration between 0.75-5.5 m depth is 6414 mg/l that gives direct infiltration rate of 0.25 mm /y Fig.22. This value is the lowest in the region because the profile is near Oteibeh Lake where the sediments are very fine clay.

7.5.3. Nitrate and ammonia concentration

Fig.25 shows Nitrate concentration is 50 mg/l at surface and decreases to 12 mg/l at 1 m depth, then decreases gradually till 1 mg/l at 3.5 m depth.
Ammonia concentration is 18 mg/l at surface and decreases till 12 mg/l at 5.5 m depth.

Table 3- Chemical data (profile A).

n°	Depth (fromto cm)	Depth (cm)	H %	Cl (mg/l)
A1	20-30	25.00	10.05	3136.72
A2	45-55	50.00	17.81	1733.14
A3	70-80	75.00	19.26	1534.46
A4	95-105	100.00	18.94	1699.09
A5	120-130	125.00	17.35	1892.65
A6	145-155	150.00	17.84	1509.35
A7	170-180	175.00	17.57	1831.57
A8	195-205	200.00	18.33	1289.85
A9	220-230	225.00	24.66	1225.08
A10	245-255	250.00	30.94	891.52
A11	270-280	275.00	26.87	1086.67
A12	295-305	300.00	21.24	1433.20
A13	320-330	325.00	18.26	1667.10
A14	345-355	350.00	23.30	1173.18
A15	370-380	375.00	19.55	1429.99
A16	395-405	400.00	14.18	1927.72
A17	420-430	425.00	16.51	1317.00
A18	445-455	450.00	17.59	1448.05
A19	470-480	475.00	20.75	1077.83
A20	495-505	500.00	21.63	1120.15
A21	520-530	525.00	23.00	1053.42
A22	545-555	550.00	18.62	1334.59
A23	570-580	575.00	20.05	1270.39

It is observed that the superficial part of profile till 1 m depth there is decreases in Nitrate concentration by denitrification and becomes Ammonia or other Nitrate components. This denitrification continues from 1-3.5 m depth. The unsaturated zone plays an important role of self-purification of infiltrated water because of low infiltration rate and a protection zone of the aquifer.

7.6. **Profile K:** (Table 6)

It was drilled in Oct. 1998 with a depth of 5.25 m and 25 cm step intervals. It is located to the west of Kharabo.

7.6.1. Humidity

At surface the humidity is 10% and increases to 25% at 2.5 m depth, then it decreases to 15% at 4.75 m. At 5.25 m it reaches 23% (Fig.23). Field observations indicate the homogeneous in sediment.

7.6.2. Chloride profile

At 25 cm, Chloride concentration is 1700 mg/l, then decreases to 600 mg/l at 75 cm and varies between 800 mg/l at 1 m to 400 mg/l at 5.25 m depth (Fig.24). The upper part of profile presents the evaporation zone. The mean Chloride concentration in the lower part is 617 mg/l that gives a direct recharge rate of 2.6 mm/y.

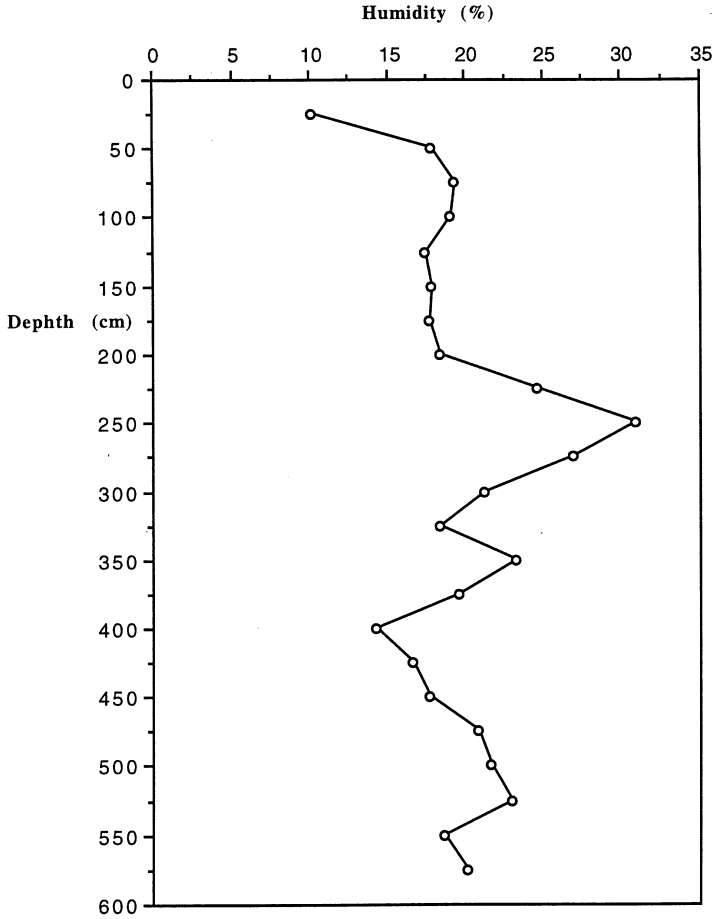

Fig.17-Relationship between humidity and depth (Profile A).

7.6.3. Nitrates and ammonia profiles

The Nitrate concentration reaches 50 mg/l at surface layer, then decreases to 10 mg/l at 1m depth and at 2.75 m depth it decreases to 1 mg/l (Fig.26). The Ammonia concentration is occurred in the surface layer of profile till 1m depth as in profile E. This zone plays very important role in Nitrate denitrification and self-purification of water. Whereas zone of 1–2.75 m depth play a less important role in perification.

The Ammonia concentration increases at 1 m and 2.75 m depth that indicates a part of Nitrates becomes Ammonia.

It is considered that Nitrates have not any pollution effect on the aquifer that has more than 5 m depth where the unsaturated zone is a self-purification zone. However, if the aquifer is more close to surface, high Nitrates concentration will pollute the groundwater.

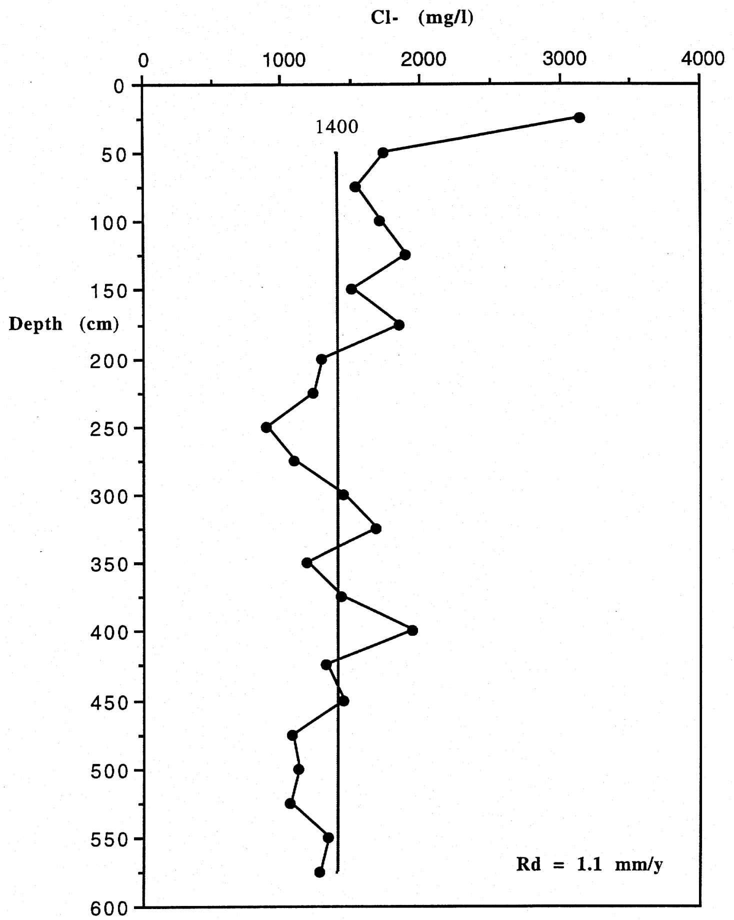

Fig.18-Relationship between chloride and depth (Profile A).

7.7. L and C profiles: (Table 7)

These two profiles were drilled at 1.5 and 1.75 m depth because of very hard soil and big gravel that prevent the drilling process. Profile L is located in the western part of the studied area. Profile C is located to the east of Damascus International Airport. The purpose of drilling these two profiles is to study the lateral distribution of the direct infiltration rate.

7.7.1. Humidity

In profile L, the humidity increases from 4% at the surface to 16% at 1.5 m depth (Fig. 27). In profile C it increases from 6% at surface to 16% at 25 cm and decrease to 10% at 50 cm depth, then it reaches 25% at the end of profile. (Fig. 29)

Table 4- Chemical data (profile B).

n°	Depth (fromto cm)	Depth (cm)	H %	Cl (mg/l)
B1	0-10	0.00	7.22	7277.01
B2	20-30	25.00	11.08	3912.05
B3	45-55	50.00	11.74	2405.47
B4	70-80	75.00	11.56	2045.24
B5	95-105	100.00	11.62	1299.94
B6	120-130	125.00	9.91	1656.79
B7	145-155	150.00	13.03	1310.48
B8	170-180	175.00	13.89	1182.06
B9	195-205	200.00	15.24	1120.44
B10	220-230	225.00	19.40	677.06
B11	245-255	250.00	20.58	765.89
B12	270-280	275.00	11.49	1143.17
B13	295-305	300.00	16.36	1043.73
B14	320-330	325.00	18.29	933.60
B15	345-355	350.00	14.78	888.70
B16	370-380	375.00	23.65	722.01
B17	395-405	400.00	24.34	809.47
B18	420-430	425.00	31.93	719.90
B19	445-455	450.00	32.95	777.34
B20	470-480	475.00	27.22	844.46
B21	495-505	500.00	28.99	906.17

7.7.2. Chloride profiles

In profile L, the Chloride concentration is 3200 mg/l at surface and decreases gradually to 600 mg/l at 75 cm then reaches 500 mg /l at the end of profile (Fig. 28). The mean Chloride concentration is 566 mg/l that gives a mean direct infiltration rate of 2.8 mm/y through unsaturated zone.

In profile C, the Chloride concentration is 5400 mg/l at surface and decreases to 2200 mg/l at 25 cm, then increases to 4300 mg/l at 50 cm, and decreases to 1500 mg/l at 1,25 m depth (Fig.30). The mean Chloride concentration is 1509 mg/l that gives a direct infiltration rate of 1.1 mm/y.

7.8. Profile H: (Table 8)

It is located in the Syrian coast to the south of Tartous city near Hamidieh village. It has 2.3 m depth and will be used for comparing the direct infiltration rate between the coastal area and Damascus city.

7.8.1. Humidity

At surface the humidity is 7% and increases to 21% at 2.3 m, then reaches 28% at 1.5 m depth because of clay layers with high humidity ratio (Fig.31).

7.8.2. Chloride profile

The Chloride concentration is 3500 mg/l at surface, then decreases to 1300 mg/l at 50 cm till 170 cm depth. At 210 cm it reaches 2800 mg/l, this increases could be the cause of seawater intrusion to groundwater in the region.

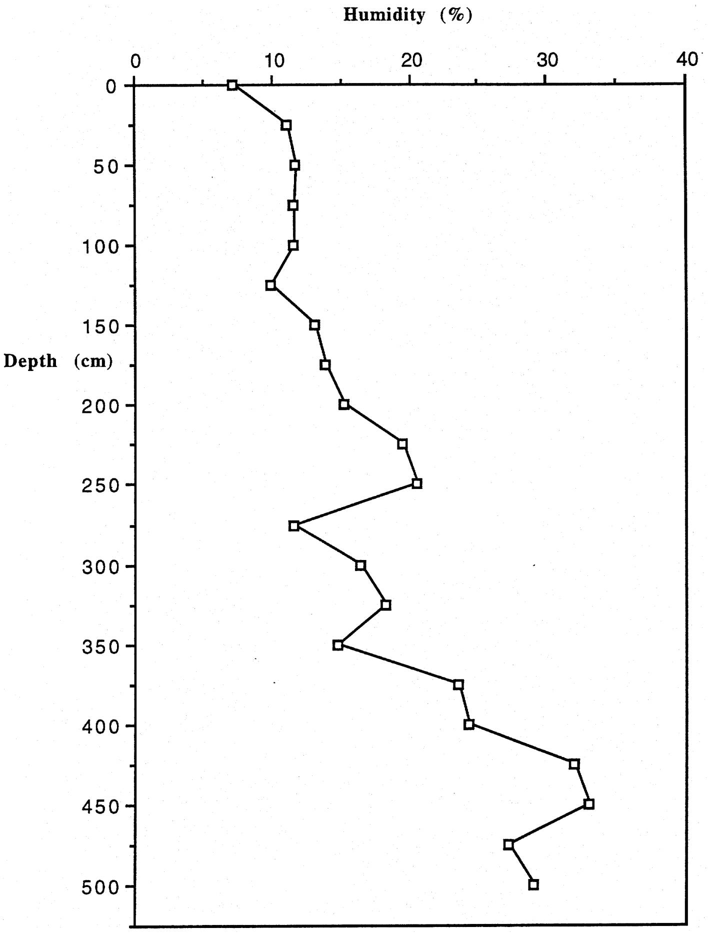

Fig.19-Relationship between humidity and depth (Profile B).

The mean Chloride concentration is 1290 mg/l from 50-170 cm depth. As the mean rainfall is 885 mm/y and the Chloride concentration in precipitation for the year 1990,1991 and 1992 is 21.26 mg/l, the infiltration rate is 14.6 mm/y (Fig. 32).

8. Spatial variations of direct infiltration rate

The following table summarizes the estimation of direct infiltration rate through unsaturated zone that could reach and recharge the shallow aquifer. Depending on the Chloride balance the following values were estimated:

Profile	P mm	Cpmg/l	C_R mg/l	Rd mm/y
Pro. I	220	7.25	876	1.8
Pro. N	220	7.25	1000	1.6
Pro. A	220	7.25	1400	1.1
Pro. B	220	7.25	988	1.6
Pro. E	220	7.25	6414	0.25
Pro. K	220	7.25	617	2.6
Pro. L	220	7.25	566	2.8
Pro. C	220	7.25	1509	1.1
Pro. H	885	21.26	1290	14.6

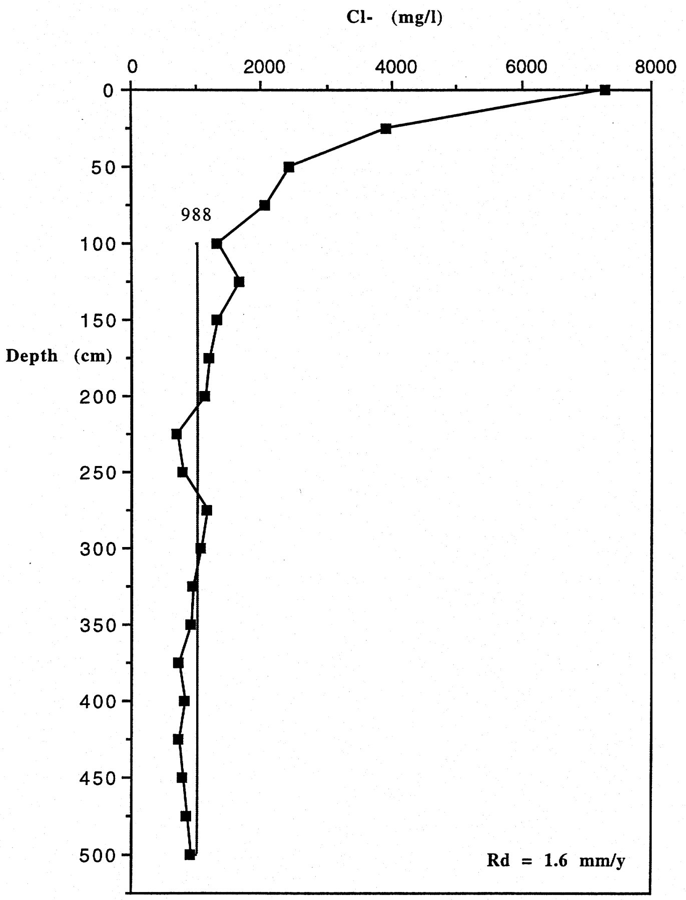

Fig.20-Relationship between chloride and depth (Profile B).

Table 5- Chemical data (profile E).

Depth (cm)	H %	Cl (mg/l)	NO3- mg/l	NH4+ (mg/l)
0.00	4.06	32789.41	47.90	18.20
25.00	8.78	17790.43	36.40	15.50
50.00	9.04	16297.01	32.80	14.10
75.00	11.73	10592.50	21.10	13.30
100.00	11.45	9843.89	12.30	13.60
125.00	12.76	8485.50	12.00	13.90
150.00	14.43	7564.97	10.70	13.10
175.00	16.10	6956.68	8.80	13.30
200.00	20.29	6902.29	6.80	11.70
225.00	22.50	6484.67	6.00	12.20
250.00	15.50	7351.94	5.70	12.80
275.00	9.26	6938.98	3.60	12.20
300.00	24.78	5314.97	3.60	10.60
325.00	24.25	6148.45	2.20	11.10
350.00	25.31	6143.42	1.10	11.40
375.00	24.85	5428.57	1.60	12.50
400.00	22.68	6934.08	0.80	13.30
425.00	19.33	5968.70	1.40	14.10
450.00	19.79	5829.96	0.80	13.60
475.00	24.05	3690.23	0.80	12.80
500.00	15.37	4965.84	0.00	13.90
525.00	15.29	3935.42	0.60	12.80
550.00	20.41	2817.74	1.40	12.50

The direct infiltration rate is varied from 0.25 mm/y and 2.8 mm/y in the studied area (Fig. 2). Generally, it is observed two parts; one is located to the western side of Damascus oasis (west of Der Al-Assafir) where the infiltration rate is more than 2 mm/y and the other eastern part where the direct infiltration rate is less than 2 mm/y and the least near Oteibeh Lake. The geological map (Fig. 1) indicates the lithological variations from west of Kharabo and divided between eastern clay area and western sandy area. And this limit is identical with the limit between the eastern and western infiltration rate parts.

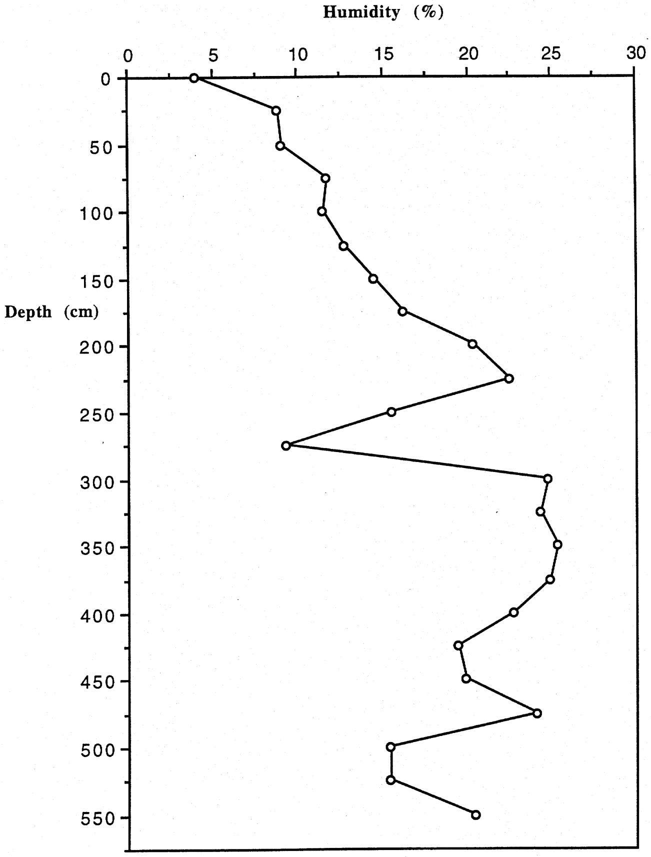

Fig.21-Relationship between humidity and depth (Profile E).

The direct infiltration rate is related to granulometry and mineralogy of soil. To the east, the sediments are more fine and clay with low infiltration rate, in contrary, to the west the sand ratio increases with high infiltration rate.

It is observed the direct infiltration rate of the Syrian coast is more by ten times than that of Damascus oasis.

9. Conclusion

The following results are obtained:

(1) The granulometry and mineralogical analysis of studied profiles indicate the alternation of sedimentation periods characterized by successive of wet climatic conditions, where the chemical erosion is dominant with high fine sediments and carbonatic minerals rate, and relatively dry climatic conditions that the aeolian erosion is dominant with high sand ratio and quartz mineral rate.

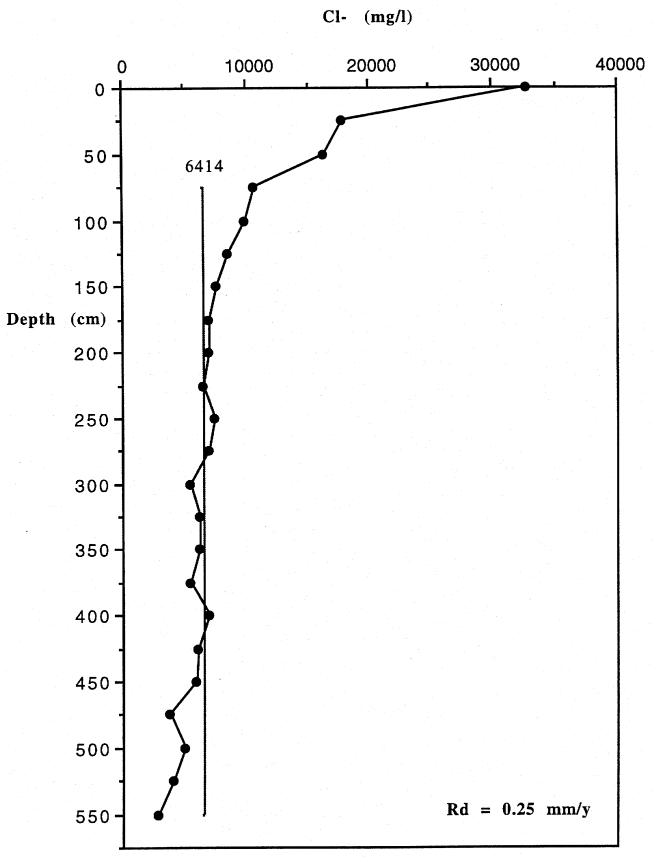

Fig.22-Relationship between chloride and depth (Profile E).

Table 6- Chemical data (profile K).

Depth (cm)	H %	Cl (mg/l)	NO3- mg/l	NH4+ (mg/l)
0.00	9.93	929.51	38.60	13.90
25.00	10.29	1724.98	35.60	15.20
50.00	13.50	1051.85	50.40	14.40
75.00	15.10	623.01	33.40	15.00
100.00	15.54	810.97	10.70	21.50
125.00	18.09	706.47	8.80	17.40
150.00	15.61	784.59	7.10	13.90
175.00	17.71	681.54	5.20	14.10
200.00	21.79	545.78	4.40	13.10
225.00	22.44	506.24	2.20	14.40
250.00	24.79	393.81	4.10	12.80
275.00	21.70	515.32	0.60	16.90
300.00	19.74	557.50	1.10	15.80
325.00	19.08	604.69	0.30	13.90
350.00	17.21	618.83	0.30	14.10
375.00	18.50	604.46	1.40	13.60
400.00	17.40	561.06	1.10	12.80
425.00	18.32	629.78	0.80	12.80
450.00	14.88	763.44	0.00	11.70
475.00	14.50	771.21	0.60	12.50
500.00	21.40	580.61	0.60	12.80
525.00	23.46	469.10	1.10	12.20

(2) Profile I was divided into superficial part from 0 to 12–14 m depth that gives direct vertical infiltration rate of 1.8 mm/y which is similar to other values in other profiles. However, the lower part from 12-14 m to 21 m depth where the infiltration rate was more than double of the recent rate, 3.5 mm/y or 5.9 mm/y. This was occurred in relatively wet climatic conditions and the mean rainfall was about 423 mm/y and 682 mm/y respectively. The wet period time was estimated, depending on the effective velocity of direct infiltration calculated by Tritium evaluation, of about 432 y or 504 y extended to more than 760 years.

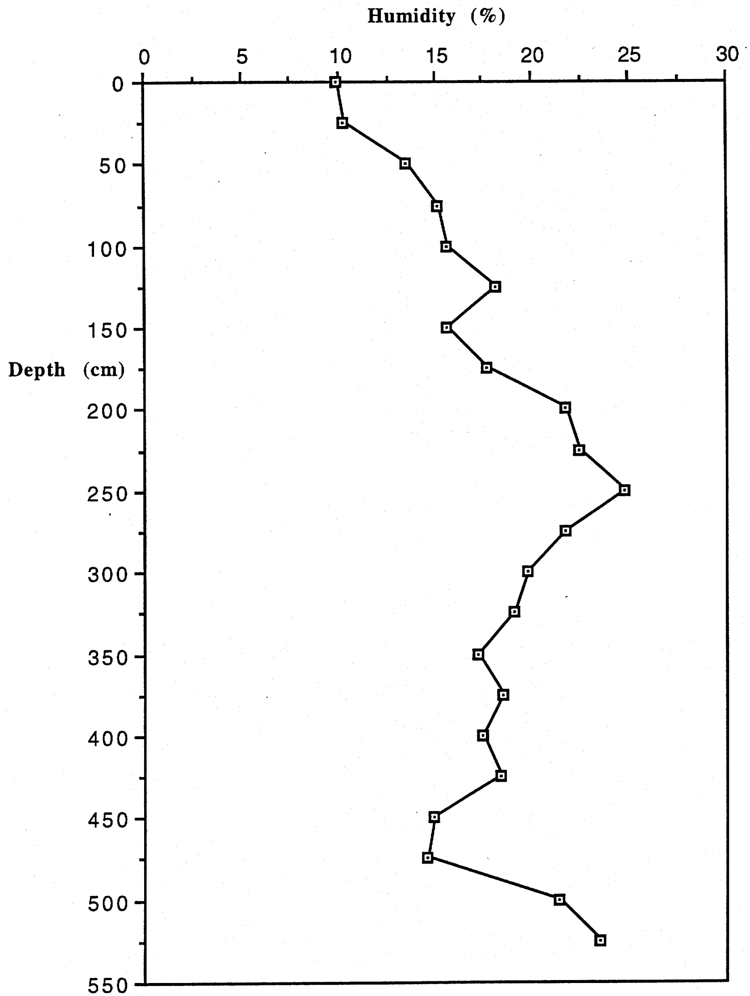

Fig.23-Relationship between humidity and depth (Profile K).

(3) The evaporation rate through the unsaturated zone, in profile (I), by applying Barnes & Allison model was estimated of 5 mm/y for the zone of dominant vapor transfer phase and 6.4 mm/y for the zone of dominant liquid transfer phase. The enrichment peak is located at 40 cm depth.

(4) The effective velocity of direct infiltration rate through unsaturated zone, depending on the Tritium peak at 1 m depth, was estimated about 27.8 mm/y or $8.8*10^{-10}$ m/s. That indicated the low infiltration rate because the soil are consisted of clay and fine loam. The mean effective porosity is 6.5% and the permeability parameter K is $0.6*10^{-10}$ m/s that characterized the unpermeability of the very fine soil.

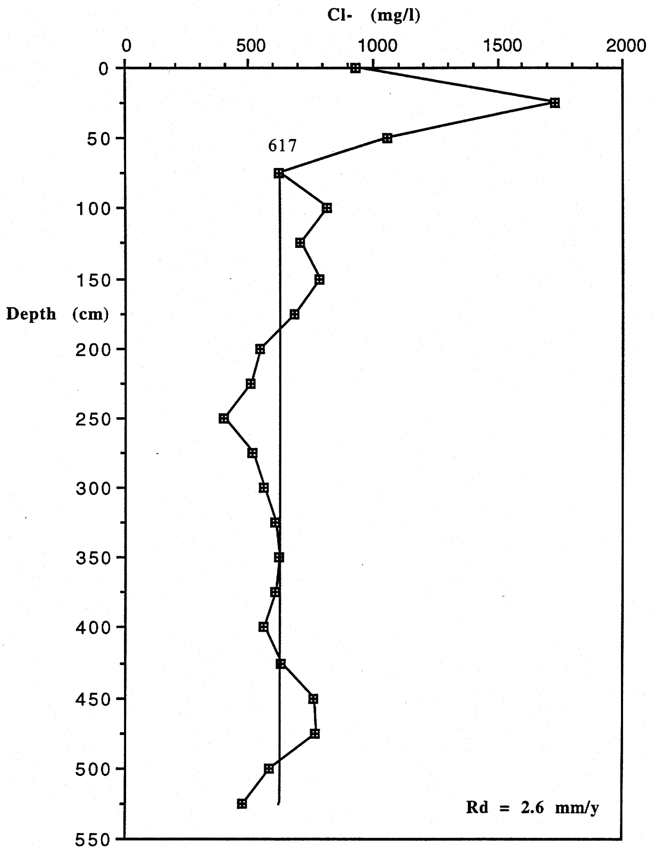

Fig.24-Relationship between chloride and depth (Profile K).

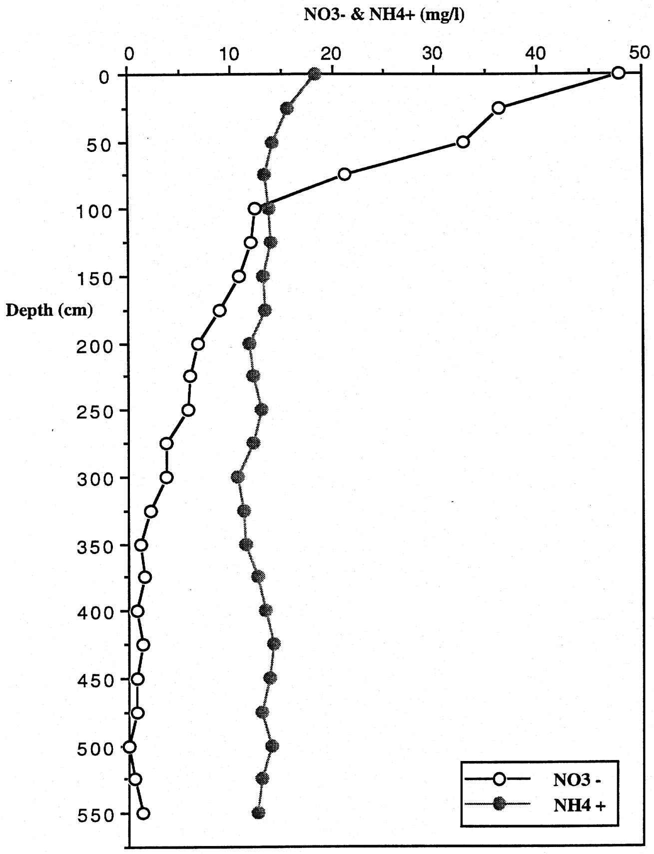

Fig.25-Relationship between NO3-, NH4+ and depth (Profile E).

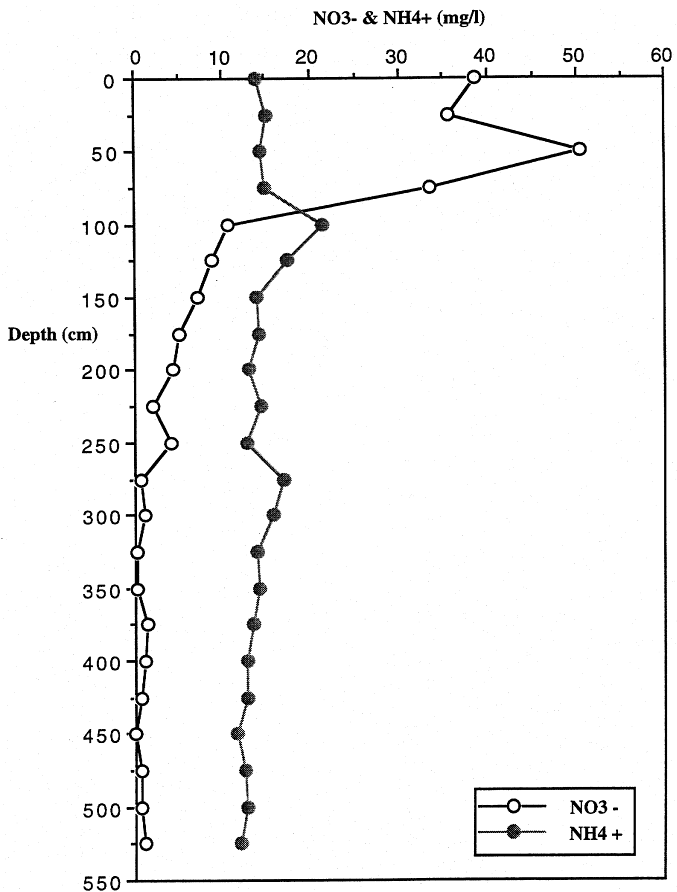

Fig.26-Relationship between NO3-, NH4+ and depth (Profile K).

Table 7- Chemical data (profile L and C).

n°	Depth (fromto cm)	Depth (cm)	H %	Cl (mg/l)
L1	0-10	0.00	3.86	3172.93
L2	20-30	25.00	8.19	1235.35
L3	45-55	50.00	10.86	1078.73
L4	70-80	75.00	15.24	656.89
L5	95-105	100.00	15.78	647.91
L6	120-130	125.00	15.38	574.74
L7	145-155	150.00	16.51	387.04
C1	0-10	0.00	5.94	5378.79
C2	20-30	25.00	16.11	2423.96
C3	45-55	50.00	10.24	4333.50
C4	70-80	75.00	10.56	4202.18
C5	95-105	100.00	12.40	3149.19
C6	120-130	125.00	24.01	1537.69
C7	145-155	150.00	24.87	1491.66
C8	170-180	175.00	22.03	1498.64

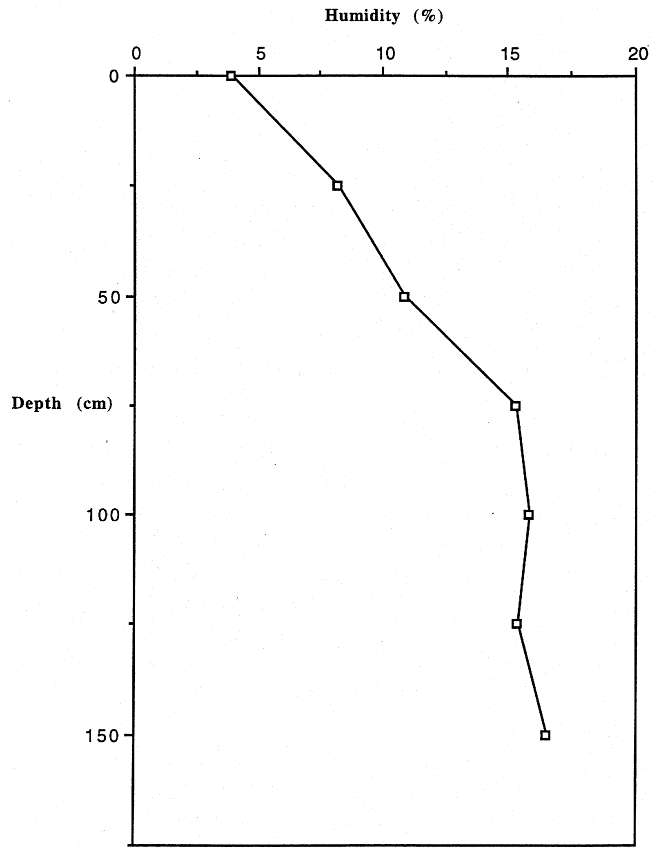

Fig.27-Relationship between humidity and depth (Profile L).

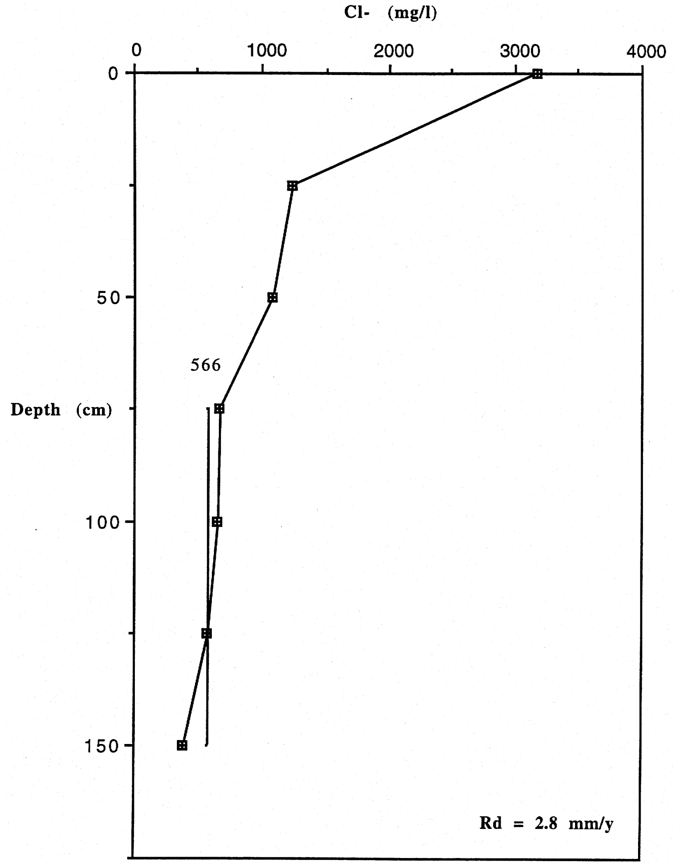

Fig.28-Relationship between chloride and depth (Profile L).

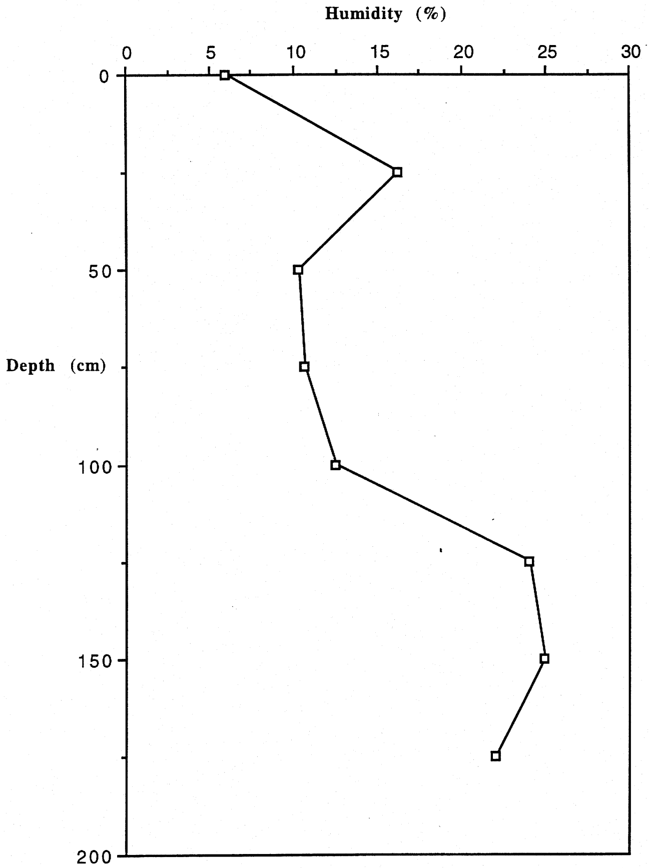

Fig.29-Relationship between humidity and depth (Profile C).

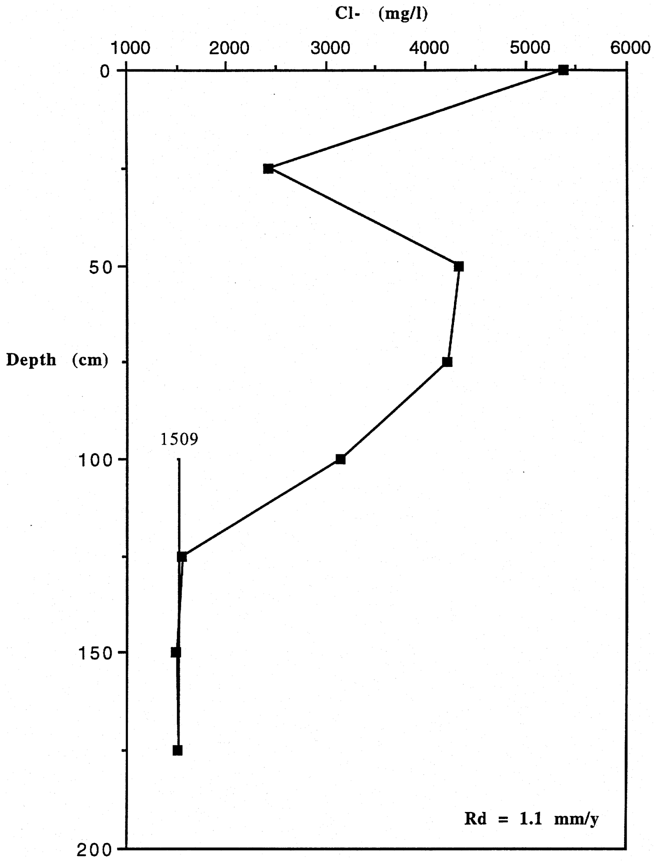

Fig.30-Relationsip between chloride and depth (Profile C).

Table 8-Che. data (pro. H)

H1	0-5	2.50	7.47	3540.50
H2	5-10	7.50	8.48	2469.93
H3	12-18	15.00	11.40	2584.65
H4	25-35	30.00	14.42	1464.81
H5	45-55	50.00	16.33	1304.35
H6	65-75	70.00	17.24	1297.27
H7	85-95	90.00	20.13	1155.12
H8	105-115	110.00	18.08	1364.63
H9	125-135	130.00	18.37	1265.79
H10	145-155	150.00	28.30	815.37
H11	165-175	170.00	20.40	1653.19
H12	185-195	190.00	19.56	2568.12
H13	205-215	210.00	19.36	2759.68
H14	225-235	230.00	20.87	833.49

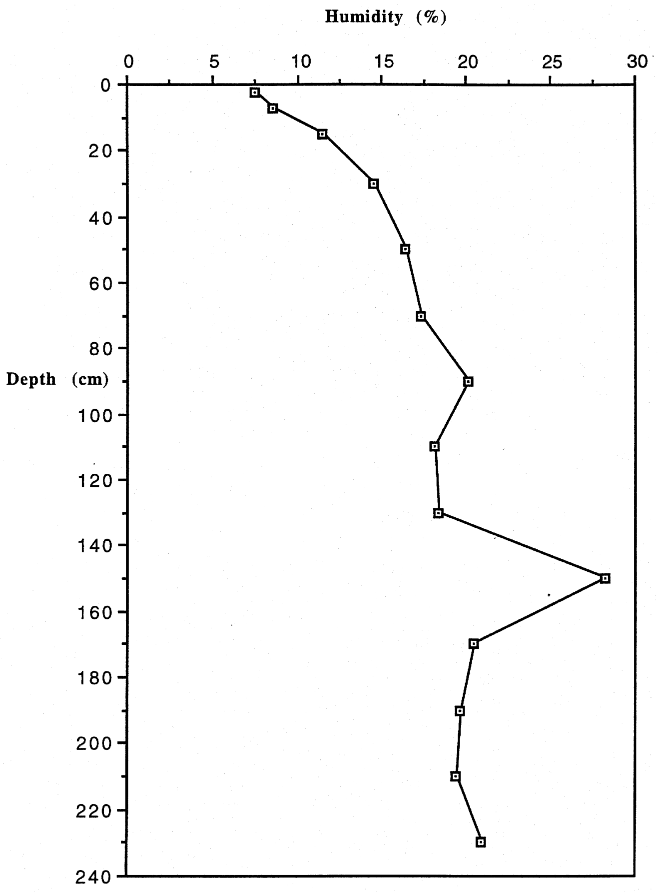

Fig.31-Relationship between humidity and Depth (Profile H).

(5) The spatial distribution of the direct infiltration in the studied area is varied between 0.25 mm/y and 2.8 mm/y. It is distinguished between a western part in the west of Damascus oasis (west of Der Al-Assafir) where the direct infiltration rate is more than 2 mm/y. And an eastern part, where the direct infiltration rate is less than 2 mm/y, and the least near Oteibeh Lake. The spatial distribution is related to the mineralogy and granulometry of soil and the lateral lithological variations. Towards the east the sediments become fine clayey and the direct infiltration rate is less, however, towards the west the sand ratio increases with increasing infiltration rate.

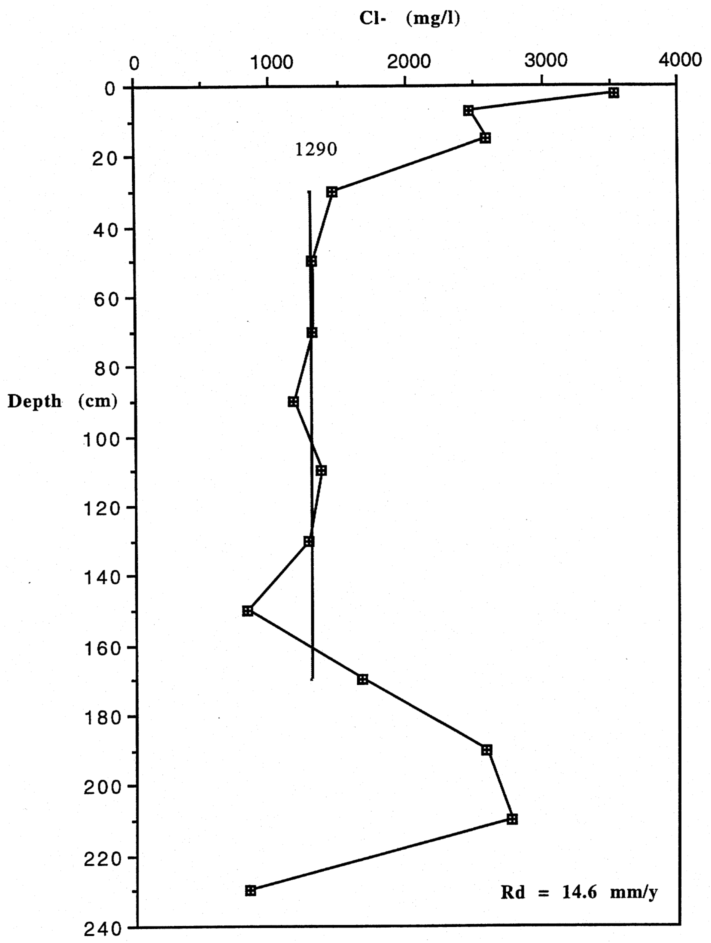

Fig.32-Relationship between chloride and depth (profile H).

(6) In the Syrian coast, the direct infiltration rate is ten times higher than that of Damascus oasis.

(7) The Nitrate pollution is restricted to the superficial part of the unsaturated zone. The groundwater of more than 5 m depth is protected from pollution because of the unsaturated zone forms a protecting and purification zone of the infiltrated water. However, groundwater that has less than 5 m depth is prone to the Nitrate pollution in high concentration.

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Thanks are due to all involved partners in the unsaturated zone study project for great atmosphere and good cooperation that lead to a complete teamwork in this regard.

Finally, we wish to thank Mr. y. Jubeli, head of Geology Det., and all staff of the Geology dept., we acknowledge Ms R. Saadah for the map drawing.

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Isotope based assessment of groundwater recharge and pollution in water scarce areas: A case study in Jordan

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Abstract. The study of environmental chloride, deuterium and nitrate has been carried out in sand profiles in two locations in Jordan. The first location is in the Quaternary sediments and sandstone's of Al Quwayra in southern Jordan where the average rainfall is less than 70 mm per year. The study concluded that there is no modern recharge in the studied site in southern Jordan. The second location is in the Kurnub sandstone outcrop near to Jarash in northern Jordan. The average rainfall in the area is 500 mm per year and thus significant recharge is possible in that area. The study showed that the annual recharge to the aquifer in that area is about 28 mm per year. The third location consists of four cores is in the alluvium Mudflat deposits of Azraq Oasis. The average rainfall in this area is about 67 mm per year which occur as storms between January and March.

1. Introduction

1.1. Background

Jordan has an area of 96000 km^2 with population of 4.5 million. The climate is wet and cool in winter (November to March) and hot dry in summer. In general the climate from west to east is transitional from Mediterranean climate to that of hot dry desert.

The climate of Jordan characterized as arid to semi-arid. The average rainfall is ranging from 500 mm over the western highs to less than 50 mm at the eastern desert.

The topography of the country characterized by the northwest highland with altitude averaging 900 m above sea level. The land slopes gently to the desert of east and south east and falls steeply to the rift valley to the west, where the Dead sea lie with altitude of about 400 m below sea level.

The water resources in Jordan are scarce, and the country depends mainly on groundwater resources for domestic purposes. The increasing demand for water requires better utilization of the country resources.

Estimation of the natural recharge of the groundwater aquifers forms the initial step in water resources management.

1.2. Importance of Azraq Basin

Azraq basin is an important water resource in the water policy of the country. The yield of AWSA wells (3 to 8 km north of Drouze springs) was 18.08 Mm^3 in 1991. The total abstraction from the basin is about 40 Mm^3/year. The pumping of a large number of wells is causing a dramatic draw-down of the local water table with consequent effect on the natural vegetation and wildlife moreover the future availability of water from this heavily exploited aquifer will be at risk. The total area of Azraq basin is about 12710 km^2 where 94% belongs to Jordan and 6% to Syria.

Azraq Oasis is located 85 km east-southeast of Amman. The study area will be mainly the Sabkah (Qa'a Azraq) which forms the Azraq drainage basin. Two groups of springs exist at the border of the Azraq Sabkah; The Drouze springs and Shishan springs. The discharge of these springs was about 10.6 Mm^3/year before 1981. This amount was in equilibrium with the actual water balance and the interface between fresh and saline waters was in a steady state condition. With the over exploitation of the basin the discharge of the springs was dramatically affected. Drouze springs dried completely in 1986 and the Shishan springs discharge was reduced by about 80%. Another problem is the salinity of the water in Qa'a Azraq because water can leave this closed basin only by evapotranspiration and salt concentrations are highly elevated in the center of the basin [7]. Therefore a precise estimate of the amount of actual recharge is very important.

The study of the environmental chloride, nitrate, deuterium, oxygen-18 and tritium in profiles has been an efficient tool to estimate the average groundwater recharge and evaporation and to investigate pollutant transport mechanisms in the unsaturated zone especially in water scarce areas [6].

The study in Jordan is carried out within the frame of IAEA scientific program.

1.3. Objectives of the study in Jordan

- To select a potential area for the unsaturated zone field studies in Jordan.
- In southern Jordan the average rainfall is about 65 mm in the study area. The aims of the study is to provide a chronology of the recharge history and to estimate the aquifer recharge when abnormal amounts of recharge occur on an irregular seasonal or annual basis since the area is subject to occasional floods that might contribute to the total recharge that the aquifer receives.
- To estimate the aquifer recharge in northern Jordan since predominant rainfall occurs and recharge is likely in the area.
- To study the migration behavior of some pollutants through the unsaturated profile.
- To estimate the amount of actual recharge in the Azraq Oasis and the surrounding springs
- To provide valuable information to the IAEA CRP project entitled " Isotope response to dynamic changes in groundwater systems due to long-term exploitation" which will be carried out in Azraq basin in the coming years.

2. Study area

2.1. Site selection

Four sites were selected for the purpose of this study (Figure 1).

The first site **(S-1)** was at the southern part of Jordan near to Al - Quwayra district with co-ordinates: 188750 easting and 922500 northing according to the Palestine grid. This site was suitable for hand auguring, where sandstone and their weathering derivatives formed the main lithologies.

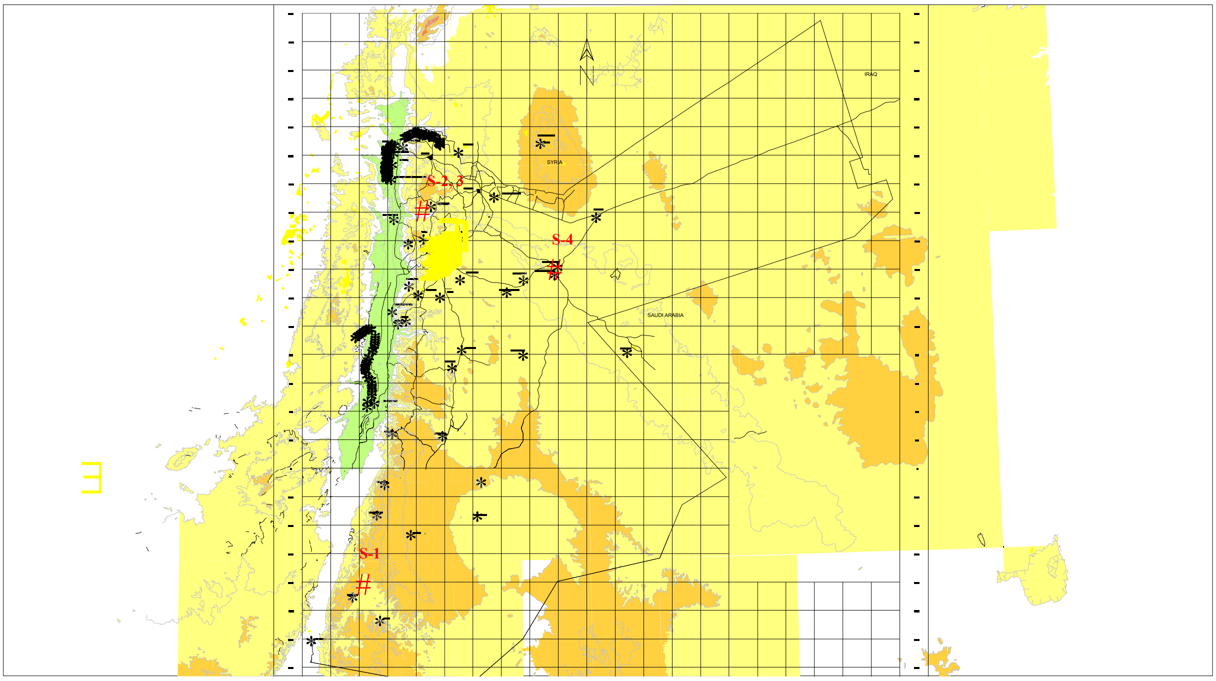


FIG. 1. Location map for sites S-1, S-2, S-3, and S-4.

The annual rainfall in the area is about 65 mm, therefore it cannot be considered as a conventional recharge area. However from the scientific point of view the study may give some information about the recharge on an irregular recharge basis. The profile could indicate the long term recharge rates as well as the possibility of providing a chronology of the recharge history. The recharge measured at S-1 location would be applicable to the whole region.

The selected S-1 site, (Figure 2) is representative of the alluvial sandy sediments forming part of a broad plain between smaller outcrops of the Umm Ishreen and Disi sandstones and with easy access to the main road [1].

FIG. 2. S-1 site (Al – Quwayra).

The second and the third sites **(S-2) (S-3)** in northern Jordan were selected in the area of Ghazza Camp west of Jarash as recommended by Mr. Ghassan Abdel Hamid from NRA who mapped this sheet. The co-ordinates are 230092 easting and 185063 northing according to the

Palestine grid. In the area the outcrop of the Kurnub sandstone forms a flat topographic feature.

The fourth site (S4) in Azraq basin. Four locations were selected for the purpose of this study:

The first location **(S4-1)** with co-ordinates 322940 easting and 143791 northing according to the Palestine grid. The static water level at a nearby well is 6.68m bgl.

The second location **(S4-2)** is near to Ora spring and is representative of the alluvial sediments with co-ordinates 323232 easting and 144197 northing. The static water level is estimated to be around 3 m bgl

The third location **(S4-3**) is next to the farms in Azraq**.** The co-ordinates are 324634 easting and 144328 northing according to the Palestine grid. The static water level at a nearby well is 4.60 m bgl.

The fourth location **(S4-4**) is at the Azraq Sabkhah which is fed by muddy floods and by natural groundwater discharge and forms the main discharge system of the study area**.** The co-ordinates are 329171 easting and 139147 northing according to the Palestine grid. Three of the sites appear in Figure 3

S4-1 (Azraq Oasis).

S4-3 (Next to Azraq farms).

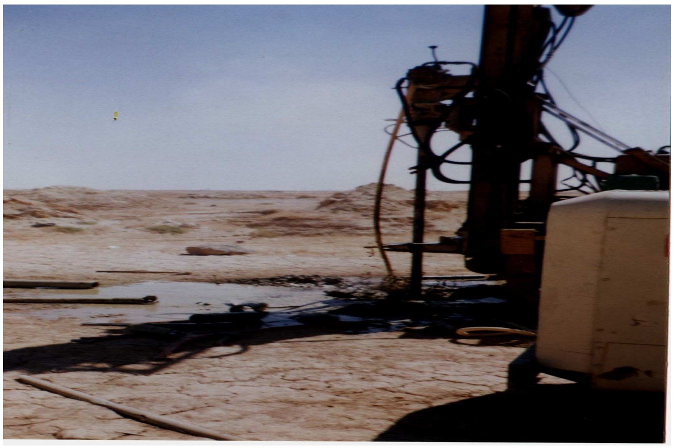


FIG. 3. S4-4 (Azraq Sabkhah or Qa'a Azraq).

From the scientific point of view the study may give some information about the recharge on an irregular recharge basis.

2.2. Geology and Lithology

Site 1 (Al Quwayra area):

The main formations in the area are the Cambro-Ordovician sandstone of the Ram Group which comprise the Salib arkosic formation, overlain by the Umm Ishreen sandstone and Disi sandstone which overlie igneous and metamorphic rocks of the Aquaba complex east of the Al - Quwayra fault (NRA sheet).

The main difference between the two formations is the presence of pebbles in the Umm - Ishreen sandstone, which is mainly red whilst the Disi sandstone is a very pure white or grey.

The sandstones are covered extensively by the Quaternary weathering. In Al Quwayra area Alluvial sands cover about 30 % [2].

The lithological description of the top 107 m of the Umm Ishrin Sandstone is shown in Figure 4.

Sites 2 and 3 (Ghazza Camp, West of Jarash):

In northern Jordan the outcrop of the Kurnub sandstone is rather limited Due to pre-Cretaceous tectonic movements, the Kurnub Sandstone Group which is the oldest formation in the study area overlies the Jurassic sequence. The sandstones are early Cretaceous mainly fine to medium grained friable red and white alternating with yellow-grey sandstone interbedded with siltstone and shale. Calcrete crust characterise some sandstone exposures in the vicinity of Ghazza camp.

The lithological description of the Kurnub Sandstone according to actual drilling (Figure 5) indicates fine to medium bedded sandstones which is locally cross-bedded with lenses of kaolinitic shale[3].

Sites 4 (Azraq):

The surface of the Azraq basin in the north-eastern half is dominated by basalts of Miocene/Oligocene age with a thickness of more than 1500m in the area of Jabal Arab. To the south of the basalt outcrop the area is dominated by Paleocene and Eocene limestones, chalks and chalky limestone of the B4 formation which is an aquifer and is covered in the center of Azraq basin by Quaternary sediments [7][8].

The first location **(S4-1)** is representative of the Alluvium Mudflat

The second location **(S4-2)** is representative of the Azraq formation which is a sequence of unconformity layers of limestone, clay, gypsum, marl, halite, and sandstone.

The third location **(S4-3**) is representative of the Abed Olivine Phyric Basalt which is a sequence of unconformity layers of basalt and sandstone with columnar and horizontal jointing.

The fourth location **(S4-4**) is representative of the Alluvial silt and siltflat.

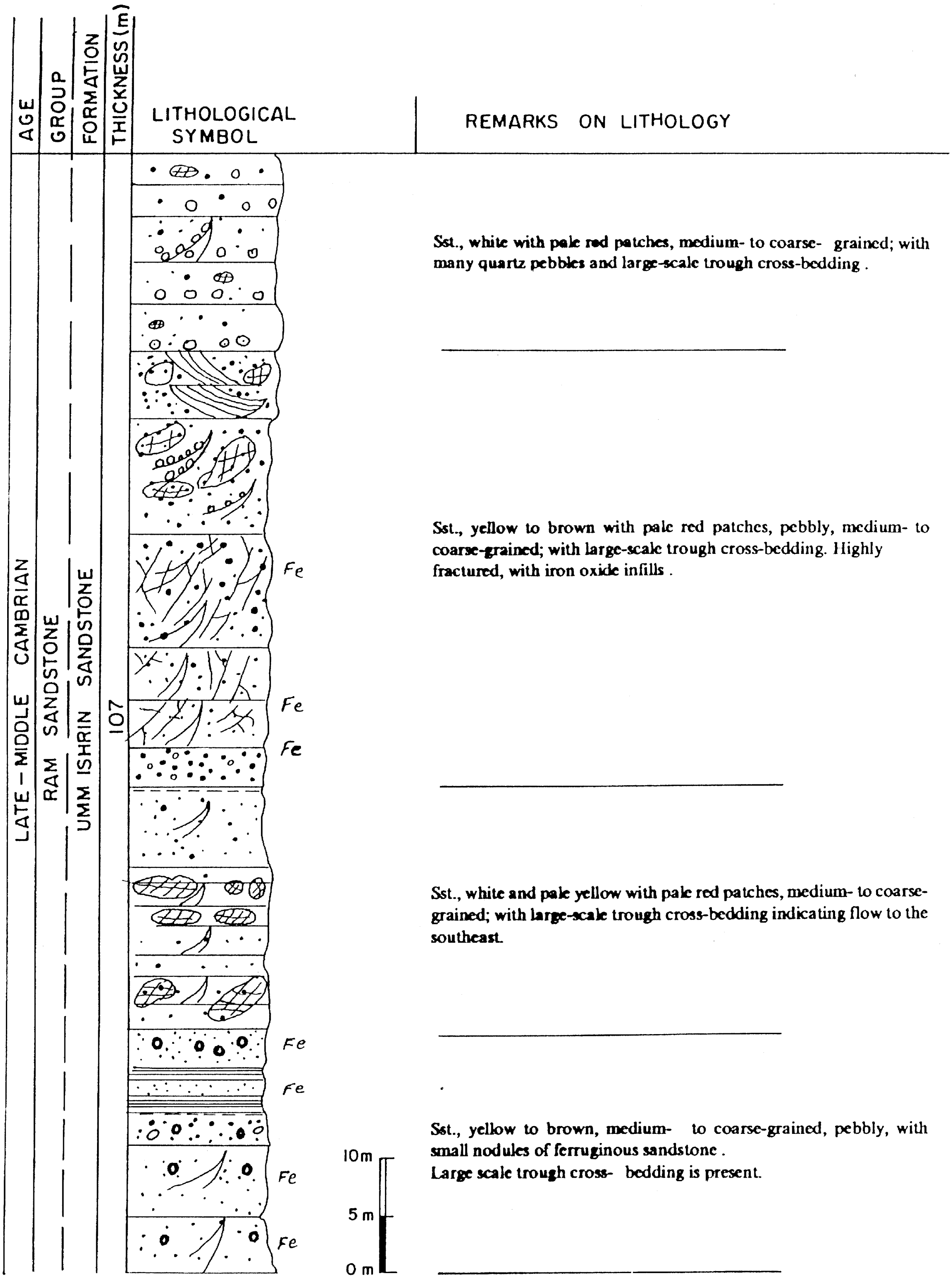
The soils in the center of Azraq basin are saline due to evaporation processes[7].

The lithological description of the Azraq formations according to actual drilling is shown in Figure 6.

2.3. Topography and climate

Site 1 (Al Quwayra area):

The lowest elevation in the area is 560 m asl and the maximum elevation is 1546 m asl on Jabal al Naqab. The topography is determined by the Al Quwayra Fault which has an easterly downthrow.



Sst., white with pale red patches, medium- to coarse- grained; with many quartz pebbles and large-scale trough cross-bedding .

Sst., yellow to brown with pale red patches, pebbly, medium- to coarse-grained; with large-scale trough cross-bedding. Highly fractured, with iron oxide infills .

Sst., white and pale yellow with pale red patches, medium- to coarse-grained; with large-scale trough cross-bedding indicating flow to the southeast.

Sst., yellow to brown, medium- to coarse-grained, pebbly, with small nodules of ferruginous sandstone .
Large scale trough cross- bedding is present.

FIG. 4. Columnar section of the top 107m (from 212 to 319m) of the Umm Ishrin Sandstone from Jabal al Mu'ays (Lat. 29°48.3'N, Long.35°22.3'E).

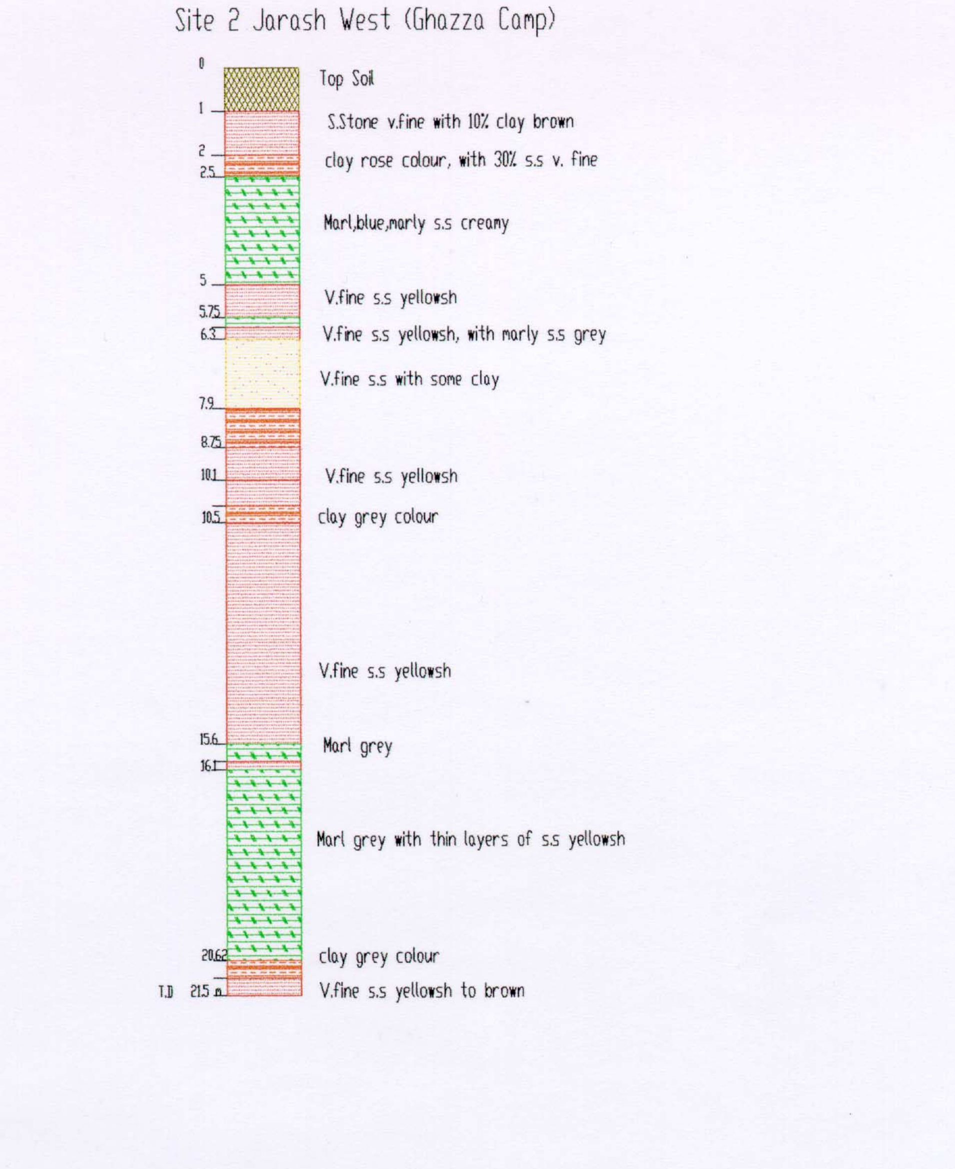
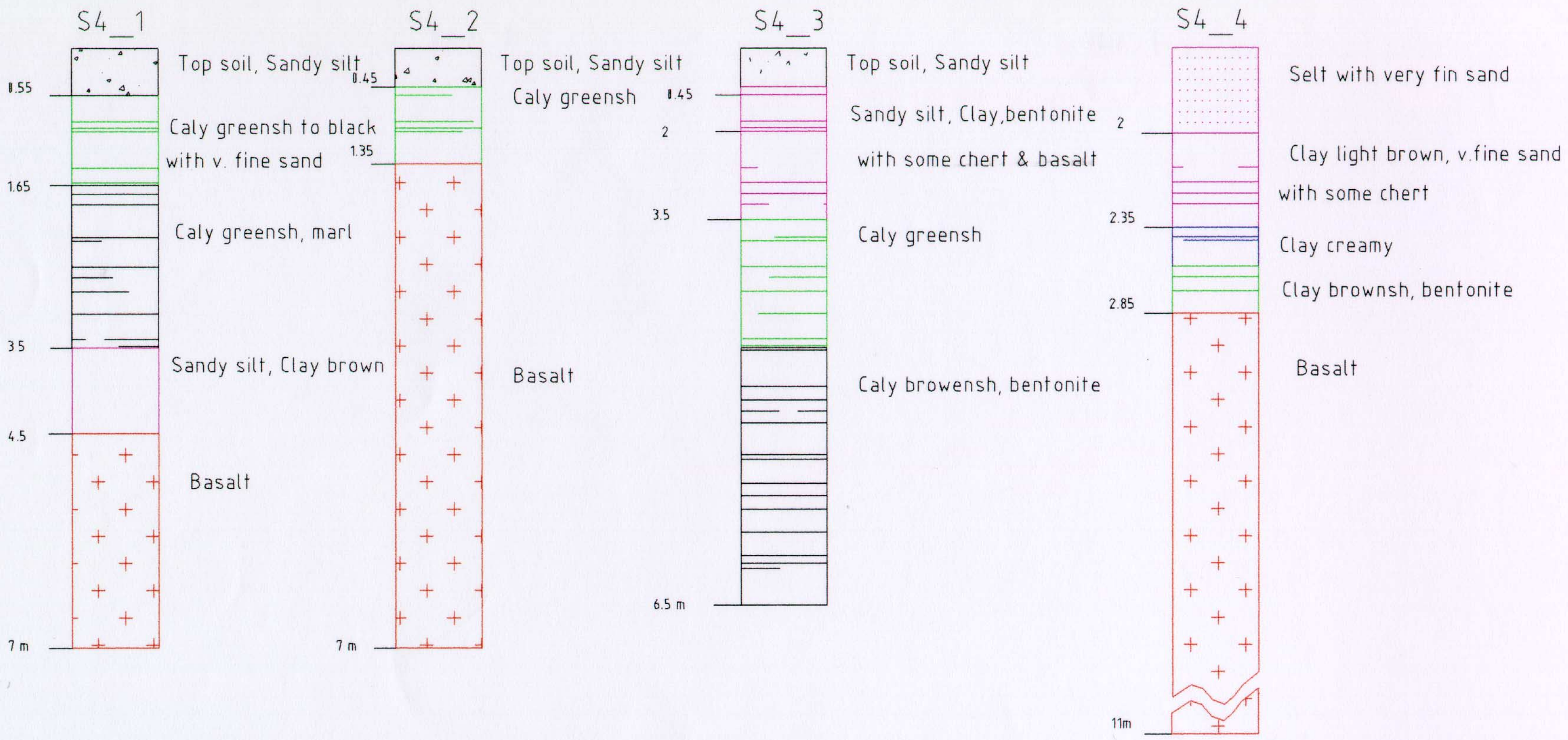


FIG. 5. The Lithological description the sandstone formation in site 2 (S-2) Ghazza Camp west of Jarash

.

The crystalline basement east of the fault has been downthrown and does not crop out. The area is flat and covered by alluvial and aeolian sand. The elevation of the study area is 953 m asl.

The climate is dry desert type. Table 1 below illustrates the average mean temperature, rainfall and relative humidity at Al Quwayra station [2].



The lithological description of the Azraq formations according to actual drilling

Figure 6

Table 1 (Climatic data for Al Quwayra area)

Parameter	Mean Annual	Mean Daily Max.	Mean Daily Min.
Temperature (C^o)	**20**	**24**	**13**
Rainfall (mm)	**65**		
Relative Humidity (%)	**45**		

Sites 2 and 3 (Ghazza Camp, West of Jarash):

The study area is part of the northern highlands. The elevation varies from 400 m asl at Wadi Jarash to 1235 m asl. Two distinctive topographic zones exists: The steep mountainous area in the central, western and southern parts and Irbid plains in the north.
The area receives a relatively high mean annual rainfall which exceeds 500 mm
Most of the precipitation is from December to March with some snowfall. The mean daily temperature in winter is less than $10C^o$. The summers are hot. The absolute maximum temperature is 35 C^o. [3]
Table 2 below illustrates the climatic data for Jarash sheet from Ras-Muneef station.

Table 2 (Climatic data for Jarash area, from Ras-Muneef)

Parameter	Mean Annual	Absolute Daily Max.	Absolute Daily Min.
Temperature (C^o)	**14.2**	**37.4**	**-4.0**
Rainfall (mm)	**547.5**		

Sites 4 (Azraq):

The Azraq basin is dissected by a dense network of wadis that acted as permanent discharge system and serves today as discharge system for the scarce floods. The Azraq Sabkhah is fed by muddy floods and by natural groundwater discharge [7].
The elevation of the locations in meters above sea level (asl) is as follows:
The first location **(S4-1)** is at 507 m asl.
The second location **(S4-2)** is at 510 m asl.
The third location **(S4-3**) is at 520 m asl.
The fourth location **(S4-4**) is at 506 m asl.
The area is typical for arid to semi arid zone. The precipitation ranges from 50 mm/year in Azraq Oasis to 500 mm/year in Jabal Arab. The average precipitation for the entire basin is 87 mm/yr. Most of which occur as storms between January to March.The mean daily temperature in winter is less than $10C^o$. The summers are hot. The absolute maximum temperature is 45 C^o.
Table 3 below illustrates the climatic data for for Azraq Area taken from Al- Azraq Al Janubi Station [8].

Table 3 (Climatic data for Azraq Area taken from Al Azraq Al Janubi Station)

Parameter	Mean Annual	Mean Annual Max.	Highest Annual Max.	Lowest Annual Min.
Temperature (C^o)	**19.1**	**26.4**	**45**	**-5.4**
Rainfall (mm)	**67.8**			
Relative Humidity (%)	**55**			
Evaporation (mm)	**11**			

2.4. Vegetation

In all the selected sites there was no vegetation cover at the time of drilling although we don’t have any record of the types of vegetation that might be present in the past.

Site 1 (Al Quwayra area):

The area is lightly vegetated. The vegetation of interest to this study is Leguminosae plants [2].

Sites 2 and 3 (Ghazza Camp, West of Jarash):

Forests cover tens of km^2 in the central, southern and western parts of Jarash sheet. Wide range of fruits and vegetables are grown partly with irrigation [3].

Sites 4 (Azraq):

The area at the four selected locations is lightly vegetated although next to S4-3 location a wide range of vegetables, fruits and olive trees is grown under irrigation [8].

2.5. Hydrogeology

Site 1 (Al Quwayra area):

The groundwater head in the study area is 250 m bgl.
The groundwater head distribution in the area is illustrated in Figure 7. The groundwater flow pattern is southwestern and is controlled by the presence of the sub-vertical Kharawi dyke, which is a natural flow barrier. The hydraulic conductivity of the aquifer according to Humphreys is 1.5 m per day. And the average porosity is 18 % [4].
According to Humphreys (1982) no natural head variations have been recorded over the last 15 years, supporting the view that modern recharge is limited.

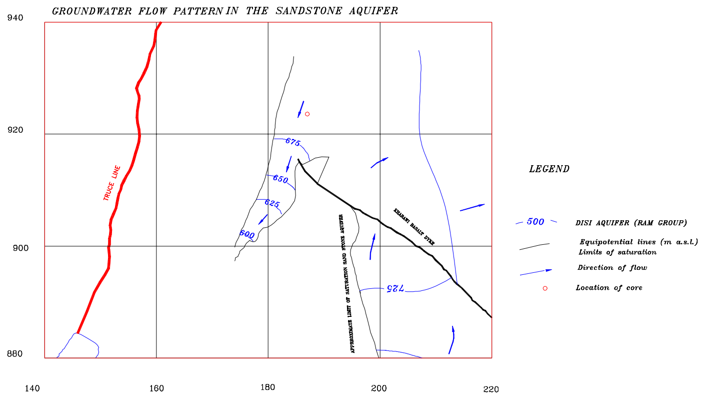


Figure 7. Groundwater flow in sandstone aquifer in south Jordan.

Sites 2 and 3 (Ghazza Camp, West of Jarash)

The groundwater head distribution in the area is illustrated in Figure 8. According to a recently drilled well which is about 1.5 km away from the studied site the water table was encountered at a depth of 15 m bgl. The pumping test gave a drawdown of 270 m and the recovery was poor indicating low permeability of the formation. The thickness of the Kurnub aquifer in the area is about 400. At the site (S-2) the water appeared at a depth of 21.5m bgl and 17m bgl at the site (S-3) where a perched aquifer in the Kurnub was encountered.

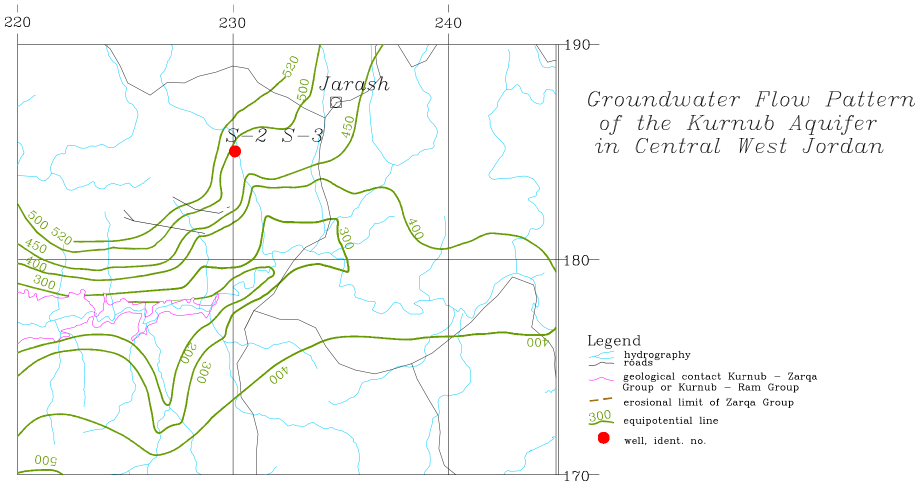


Fig. 8. (Groundwater flow pattern in Kurnub sandstone).

Sites 4 (Azraq)

The B4 aquifer is underlain by the B3 (Muwaqqar formation) of Maastrichtian age which is considered as aquitard. It is followed by the B2/A7 formation of Campanian and Turanian age that consists of cherts and limestones. The B2/A7 outcrops at the west of the catchment area. The basalts may in some areas be in contact with B4 and B2/A7 aquifers and recharge it directly [7].

The upper unconfined aquifers (Basalts, B4 and Quaternary sediments) represents the main discharge system of the study area.the discharge is radial to the Azraq oasis.The depth to the ground water table is from few meters in the center of the oasis to 400 m in the northern catchment area.

The deep B2/A7 aquifer is confined in the study area and becomes unconfined in the western and southwestern edges of the Azraq catchment. The depth to the bottom of B3 is from 260m to 720 m and SWL range from 34m to 236 m.

Groundwater contour maps have been drawn for both the upper and deep aquifers. Figure 9 shows that the shallow and the deep groundwater discharge radially to the Azraq springs. This area is important for the regional groundwater flow [7][8].

3. Field work and methodology

3.1. Sampling methodology

Sampling methodology in site 1 (Al Quwayra area)

A borehole with a depth of 10.5 m was drilled (23 to 28 August 97) using a hand auger (Dormer Engineering, Australia) which was supplied by the IAEA. The auger has a diameter of 70 cm and equipped with shear legs and pulley to assist lifting. The samples were collected each 0.25 m and kept in special metal containers which were kept in cool place to minimise moisture evaporation.

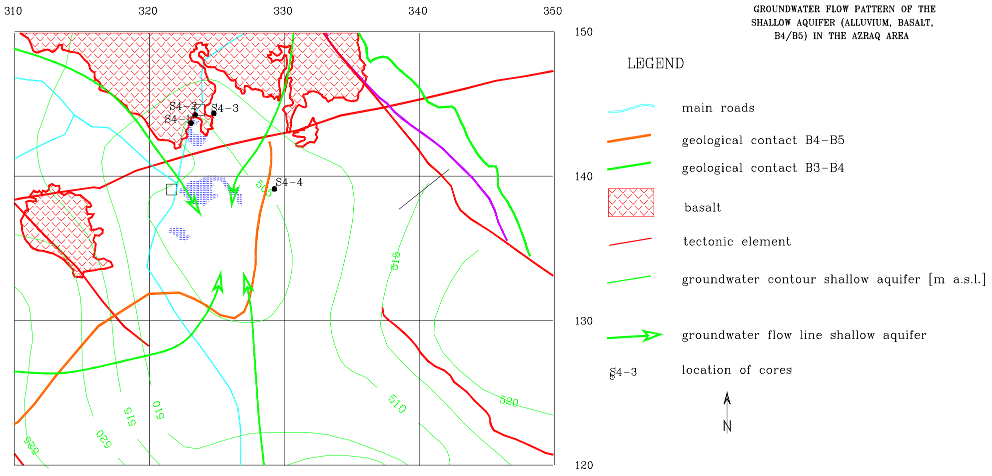


FIG. 9. (Groundwater flow pattern in the Shallow Azraq aquifers).

The topmost 75 cm were relatively dry and were difficult to maintain the recovery of the core. The lithology consisted of mainly fine to medium red brown sands and two soft white deposits. Pebbles up to 2 cm gave some auguring problems. At the depth of 10.5 m the drilling stopped completely due to solid stone or unpenetrated material that faced the auger [1].

Sampling methodology in site 2 (Ghazza Camp, West of Jarash)

Drilling and sampling in the Kurnub sandstone (November 97) was carried out using percussion air - flush rotary drilling. The depth of the core when the water table was encountered was 21.5 m.

- Sampling was carried out at 0.5 m intervals.
- Duplicate samples were taken for measurements at both the BGS and WAJ laboratories that include stable isotopes, Cl, NO_3, and humidity determination. Samples were kept for tritium measurements to be carried out in the future.

Sampling methodology in site 3 (Ghazza Camp, West of Jarash)

Drilling and sampling in the Kurnub sandstone (October 98) was carried out using percussion air - flush rotary drilling. The depth of the core when the water table was encountered was 17m.

- Sampling was carried out at 0.5 meter intervals.
- Samples were taken for measurements at WAJ laboratory that include Cl, NO_3, and humidity determination. Samples were kept for tritium measurements to be carried out in the future.

Sampling methodology in site 4 (Azraq)

The site was visited on 29 August,1999. During this visit, four boreholes locations were assigned. The first three boreholes were located in the vicinity of existing water wells in which the water level was measured at levels of 6.68, 5.0 and 5.0m, respectively, below the existing ground surface. In the area of the fourth borehole, no water wells were observed, therefore it was instructed that a stand-pipe peizometer be installed in this borehole.

During the period between Sept. 1st and 6th, 1999, four boreholes were drilled at the project site areas, the boreholes are numbered S4-1, S4-2, S4-3 and S4-4. The boreholes were drilled to depths of 7.0, 7.0, 6.5 and 11.0m below the existing ground surface, respectively.

The drilling was executed with Hand England - Drill Master 24 type drill rig using percussion and/or rotary air flush drilling methods.

Undisturbed samples throughout the soil deposits were obtained using U100 sampling system which consists of steel body tube containing a removable 45 cm long and 100 mm inner diameter plastic liner, a core catcher, a spacing ring and a case - hardened drive cutting shoe. The sampling tube was driven into the ground for 50 cm intervals, using a sliding hammer with U100 driving head. After driving the sampler for a 50 cm in the soil deposits, the sampler was pulled out from the borehole and the plastic tube containing the obtained sample was removed from the sampler and immediately sealed with wax and air-tight plastic bags to preserve the soil sample at its natural moisture content.

The above methodology was followed for sampling through the intervals from 0.0 to 4.2 m in S4-1, from 0.0 to 1.4 m in S4-2, from 0.0 to 0.5 m in S4-3 and from 0.0 to 3.4 m in S4-4. Below the above mentioned intervals, the presence of gobbles and boulder-size basalt and basalt bedrock, did not allow sampling using the U100 system.

Drilling within the basalt gobbels boulders and bedrock was carried out using triple core barrel of 76 mm inside diameter [10]. More details are included in appendix 4.

- Sampling was carried out at 0.5 m intervals.
- Samples were taken for measurements at WAJ laboratory that include Cl, NO_3, and humidity determination. Samples were kept for tritium and deuterium measurements to be carried out in the future.

3.2. Laboratory procedures

Moisture is determined by weighing 50 g of field-moist sediment which is then dried at 110 C^o for about 18 hours and weighed again. The results are then reported as % wt basis.

Cl and NO_3 are determined by elution (elutriation) of samples to extract the pore water. 50 g of sediment and 30 ml of distilled water are stirred carefully for 1 minute. After 2 hours centrifugation is used to settle fine-grained material and the supernatant solution is filtered though 0.45 μm filter [1].

Cl and NO_3 and some SO_4 measurements were carried out at WAJ laboratories using DX-120 Dionex ion chromatograph.

4. Results and discussion

To calculate the average annual recharge the following equation developed by Edmunds [1] is used:

$$\mathbf{P.\ C_p = R.\ C_R} \qquad \textbf{Equation 1}$$

Where

P	The average annual rainfall (precipitation) in mm.
C_P	The average Cl concentration in rainfall
R	The required annual recharge rate in mm.
C_R	The average corrected Cl concentration in soil in mg/l.

To determine the mean annual recharge using chloride it is assumed that the only source of chloride at the soil surface is either from rainfall or as dry deposition and there is no contribution from weathering [6 page 248].

The average Cl concentration in soil in mg/l is calculated according to the following equation:

$$\mathbf{C_R = C_{elu}\ .\ (V + m.w/100)/\ (m.w/100)} \qquad \textbf{Equation 2}$$

Where

C_{elu}	The Cl concentration in the eluate in mg/l.
V	The volume of distilled water added which is in all the cases 30 ml.
m	The moisture content in g of water/ 100 g of wet soil (wt%).
w	The weight of wet soil in g.

Equation 2 is also used to calculate the corrected nitrate concentration in soil.

Site 1 (Al Quwayra area):

The analytical results of the humidity, chloride and nitrate are shown in appendix1 and illustrated in figure 10.

The moisture content in the profiles varies between 1 to 5 wt% (figure1-Annex1). The maximum soil humidity was at a depth of 1-meter (5.7 wt%), and then decreased to about 2% and remains relatively constant throughout the profile, which reflects the homogenous lithology. Some relative increase in humidity could be observed at a depth of 5.5, 7 and 9.75 meters bgl.

Chloride and nitrate in soil water extracted by elutriation within the profile and the corresponding soil moisture contents are given in appendix1and illustrated in figures 2 and 3 inAnnex1 as a function of depth expressed in cm. The isotopic results of deuterium analyzed at the British Geological Survey laboratories, UK are illustrated in figure 11.

The chloride concentration within the profile shows a rapid increased concentration within the first 2.5 meters from the top, to reach 20×10^3 mg/l. Afterwards the concentration through the profile remains relatively constant with slight increase that ranges between 20×10^3 and 25×10^3. At these high Cl concentrations the recharge rate can be considered zero.

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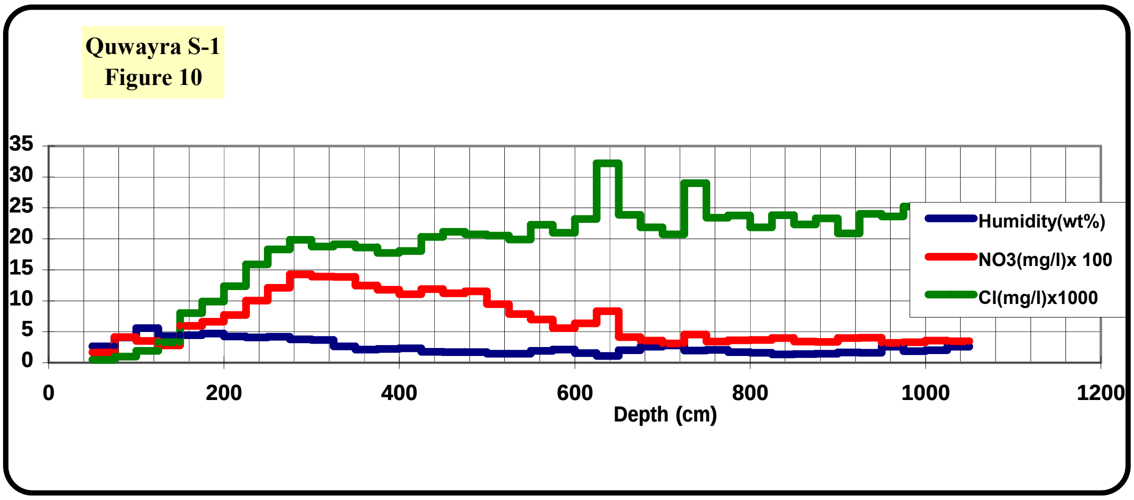

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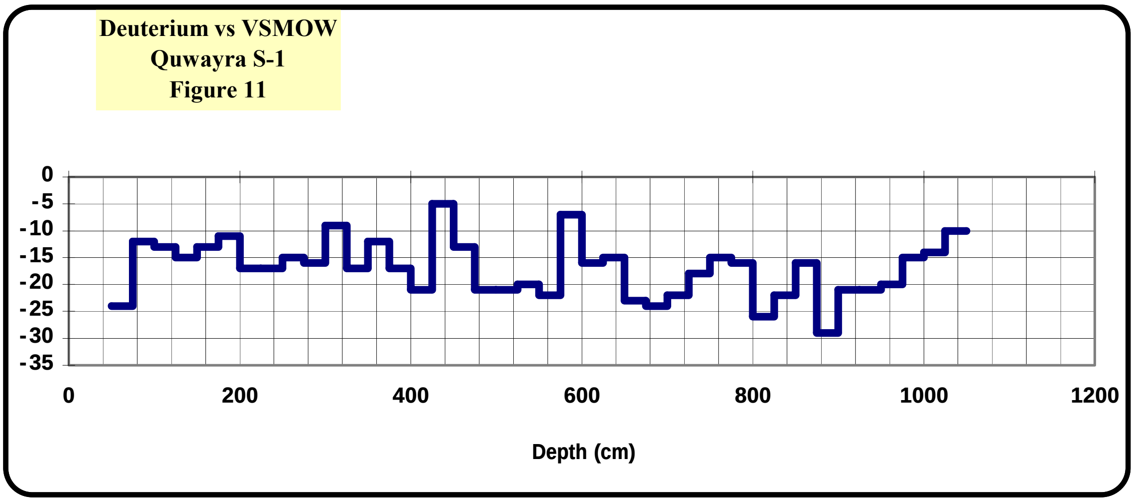


The chloride concentration within the profile shows a rapid increased concentration within the first 2.5 meters from the top, to reach $20x10^3$ mg/l. Afterwards the concentration through the profile remains relatively constant with slight increase that ranges between 20 x 10^3 and 25 x 10^3. At these high Cl concentrations the recharge rate can be considered zero.

The decrease in Cl content associated with increase in humidity at the depths of 5.5, 7 and 9.75 meters could be referred to some recharge events during floods in the past.

The nitrate trend throughout the profile shows an increase with depth to reach a concentration of 14x 10^2 mg/l at 3 meters bgl. The Leguminosae plants in the area might be responsible for the augmentation of nitrates in the profile. The NO_3 concentration drops after a depth of 3 meters. The nitrate behaves as a conservative constituent and can thus be considered as a tracer.

The profiles that were obtained during summer time have a relatively dry profile in the upper 2 meters [6].

In S-1 the deuterium profile figure 11 reveals an enrichment in deuterium together with enrichment in, Cl and NO_3 from 2 m bgl until the end of the core except at a depth of around 8m where clay might be encountered. The average annual recharge is calculated according to equation 1 where:

P	65 mm/year
C_P	10.5 mg/l
C_R	21 x 10^3 mg/l

Then

R = 0.03 mm/ year

It is concluded that there is no modern recharge in the studied site in southern Jordan.

The above conclusion is supported by a previous study conducted in 1993 where many wells that tap the sandstone aquifer were analyzed for tritium. In all the wells the tritium was less than 1 TU. Also a study by Humphreys (1982) concluded that storage depletion provided the major proportion of flows identified in the aquifer and that these are only supplemented by occasional indirect minor modern recharge[4].

Site 2 (Ghazza Camp, West of Jarash):

The soil core at S-2 was obtained using air - flush rotary drilling. Samples were collected every 0.5 meter interval to a depth of 21.5 m where saturated sand was encountered. The first meter was topsoil and thus was excluded because the area received about 20 mm of rainfall few days before the drilling process. Moreover, This horizon is considered as a part of the zone that is subject to evapotraspiration.

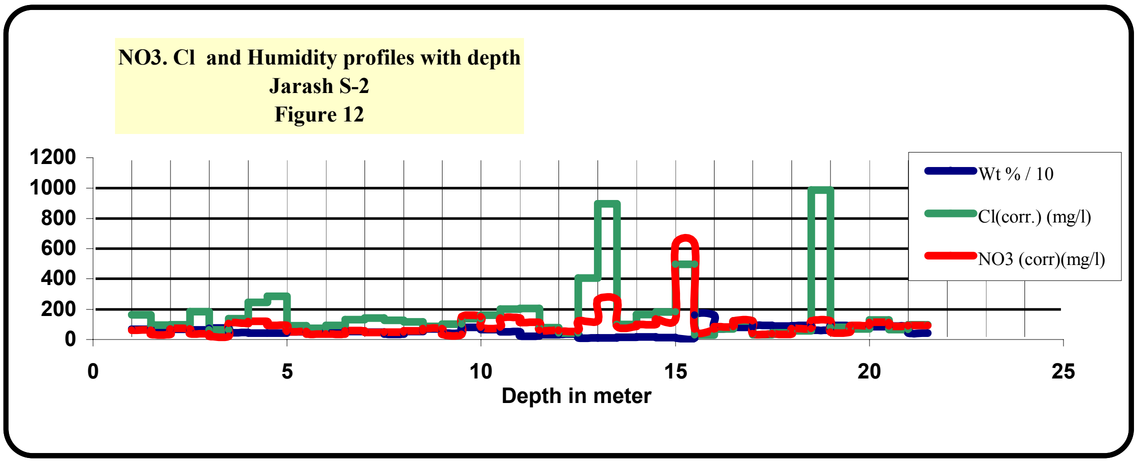
Replicate samples were collected from a single representative batch to be analyzed at the BGS, WAJ and Jordan Valley Authority Laboratories.

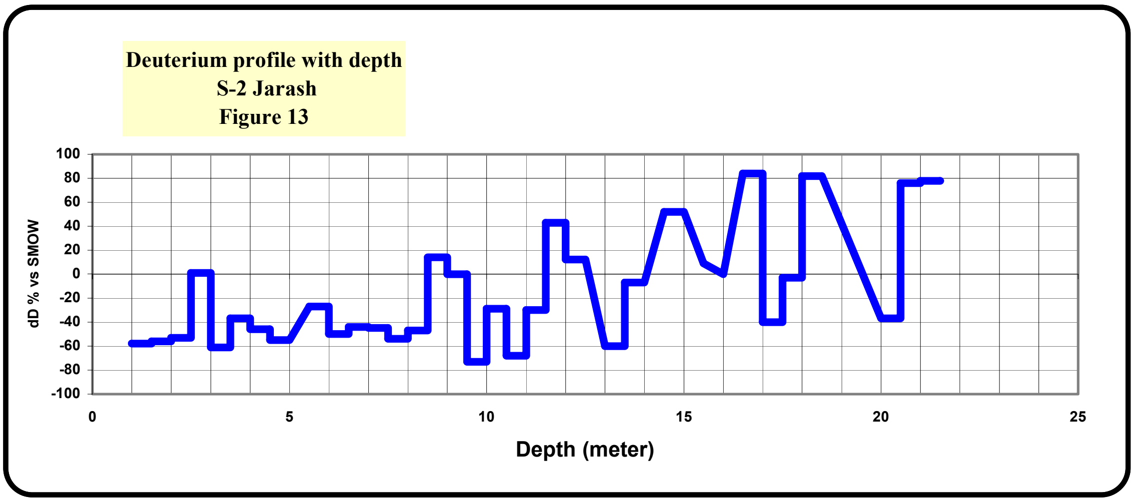
At WAJ laboratory the samples were analyzed for humidity content, Cl and NO_3.

Deuterium analyses were conducted at BGS laboratories.

Corrected soil Cl and NO_3 calculated according to equation 2.

Humidity, soil Cl and NO_3 as a function of depth (expressed in m) are given in appendix2 and illustrated in figure 12. The isotopic results of deuterium analyzed at the British Geological Survey laboratories, UK and are illustrated in figure 13.


NO3. Cl and Humidity profiles with depth
Jarash S-2
Figure 12


Deuterium profile with depth
S-2 Jarash
Figure 13

The moisture content through the depth varies between 1 and 16 wt% with an average of 6 %. figure 1-Annex2

The sudden change in moisture content between 1 and 16 % is observed at depths from 12.5 to 16 meter bgl. This reflects the different lithologies at those depths. Otherwise the soil humidity is relatively constant throughout the core with slight increase towards the bottom of the core.

The variation in Cl concentration with depth as illustrated in figure 2- Annex2 shows peaks at 13, 15 and 19 meters bgl and could be explained as change in chloride input due to atmospheric depositions or accumulations probably during past drought periods. Despite these changes, the Cl concentration remains relatively constant with depth, which indicates a steady state longterm recharge mechanism.

The nitrate concentration with depth illustrated in figure 3-Annex2 matches that of Cl indicating precise analytical results and confirming the recharge history. The average soil nitrate concentration is about 95 mg/l, which remains constant through out the core profile. The nitrate origin in the study area might be due to agricultural practices like autumn ploughing and live stock farming. A sharp NO_3 peak is observed at a 15 meter depth where thick clay layers were encountered.

In S-2 the profile represents a seasonal steady-state evaporation within the soil above the zero flux plane. Above this vapor discharge predominates and below this liquid transfer is dominant [6].

In figure 13 the enrichment in deuterium occurs at the following depths: 12, 15, 17, 18 and 21 m bgl. Depleted values with respect to the heavy isotope reflects years with higher rainfall and lower evapotranspiration. The isotopic variation represent a record of inputs from periods of wetter and drier years. The deuterium profiles correlate well with the chloride values (figure 2-Annex2) such that enrichment in the heavy isotopes corresponds to higher chloride values. This enrichment in deuterium associated with enrichment in Cl and NO_3 might be due to heat generated by the rotary drilling especially at depth which is not experienced with hand augering.

No qualitative estimate of recharge can be made using deuterium profiles because the water and its isotopic inputs are nonconservative [6].

Recharge to the aquifer occur during a small period of the year, therefore seasonal variation are not likely to be expected in the unsaturated zone and the depleted deuterium values are connected to the short but heavy rain events.

In fine sediments and in sand the infiltrated water undergoes partial evaporation thus modifying its isotopic composition [5].

To estimate the average annual recharge in the area, the average Cl concentration in rainfall should be determined. The mean weighed average of Cl concentration in Ras- Muneef {*as well as in the nearby Baqa'a station*} is calculated to be 10.23 mg/l .

The average annual recharge is calculated according to equation 1 where:

P 480 mm/year.
C_P 10.23 mg/l.
C_R 173.21 mg/l.

R = 28.35 mm / year.

The mean annual recharge value can be considered **28.4 mm per year** or about 6 % of the total amount of precipitation. Earlier water balance calculations (for a normal year) carried for Jarash sheet by WAJ hydrologists showed that recharge to the aquifer is about 7% of the total amount of rainfall [Per. con. Dr. Rakad Ta'any].

The downward movement and the residence time can be calculated using moisture content and the recharge rate. This indicates that water entering the aquifer now fell as rain years ago [6].

The movement velocity can be calculated using the following equation [9 page 537]:

Vw = Rd / (bd x mc) **Equation 3**

Where
Vw is the required rate of movement in meter/ year
Rd is the calculated recharge rate in mm/year
bd is the bulk density which is 1.5 g/cm^3 for sandy soils
mc is the moisture content in g/kg of dry sand.

For **S-2** at Jarash
Rd is calculated to be 28.4 mm / year.
mc is 60 g/ 1000 g.

Then
Vw is 31.6 cm/year.

Estimation of Aquifer Recharge and Vertical Water Movement using Deuterium Profile at S-2:

In arid and semi arid regions where recharge to the aquifers occurs only during a small periods of the year the deuterium content of the soil has been found to reflect the yearly movement of the soil moisture through the unsaturated zone. It has been possible to trace the vertical displacement of deuterium depleted – enriched profiles (dry–wet interface) so that the repeated down ward displacements of the enriched peaks during summer (dry seasons) lead to a sequence of heavy isotope peak conserved in the unsaturated zone

The sequence of these peaks from the beginning of the core excluding the uppermost 2 meters until reaching the water table revealed that soil moisture recharging the aquifer takes about 11 deuterium peaks (years) to cover the vertical distance of 19 meters. Therefore the average vertical water movement velocity is about 1.72 meter per year. The average moisture content through out the core is 6%.It can assumed that the actual moisture released from sand particles and moving downward to recharge the aquifer is about 4%. Using **equation 3** the calculated aquifer recharge rate will therefore be around 100 mm per year.

Site 3 (Ghazza Camp, West of Jarash):

The soil core at S-3 was obtained using air - flush rotary drilling. Samples were collected every 0.5 meter interval to a depth of 17 m where saturated sand was encountered. S-3 site is 150 m to the south from S-2 site.

At WAJ laboratory the samples were analyzed for humidity content, Cl and NO_3 . Corrected soil Cl and NO_3 are calculated according to equation 2. Appendix3

Humidity, soil Cl and NO_3 as a function of depth (expressed in cm) are illustrated in figure 14. The isotopic results of deuterium analyzed at the British Geological Survey laboratories, UK and are illustrated in figure 15.

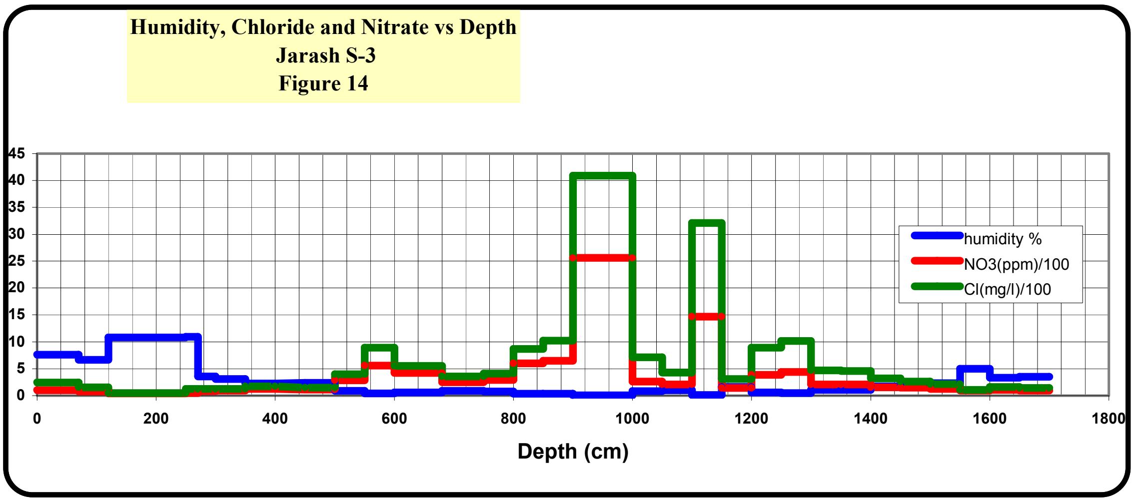
The moisture content through the depth varies between 0.08 and 10.92 wt% with an average of 2.54 %. Figure 1-Annex3

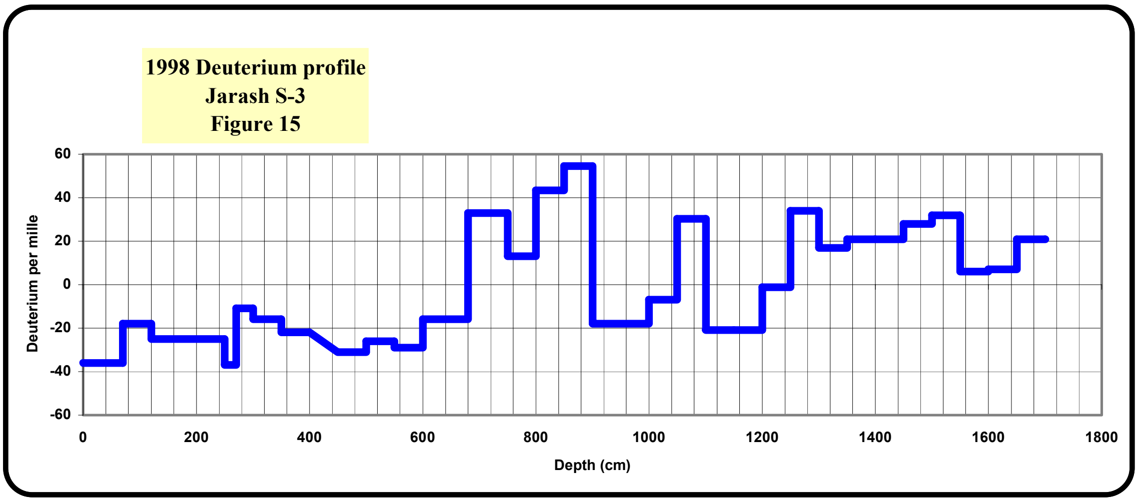
The soil humidity is relatively constant through the core with slight increase towards the bottom of the core because it's near the water table.

The variation in Cl concentration with depth as illustrated in figure 2-Annex3 shows peaks at 9, 11 meters bgl and could be explained as change in chloride input due to atmospheric depositions or accumulations probably during past drought periods.

But in general the chloride concentrations are high. the Cl concentration remains relatively constant with depth, which indicates a steady state long-term recharge mechanism.. There is a capillary fringe starting at 16 m bgl and therefore the chloride is gradually diluted by aquifer water [6].

The nitrate concentration with depth illustrated in figure 3-Annex3 matches that of Cl indicating precise analytical results and confirming the recharge history. The average soil nitrate concentration is about 349.72 mg/l, which remains constant through out the core profile. The nitrate origin in the study area might be due to agricultural practices like autumn ploughing and live stock farming.


Humidity, Chloride and Nitrate vs Depth
Jarash S-3
Figure 14


1998 Deuterium profile
Jarash S-3
Figure 15

The enriched deuterium values of S-3 figure 15 suggest that evaporation had occurred during sample handling and / or drilling. The deuterium profiles therefore cannot be used to confirm our findings at the same site in core S-2.
The average annual recharge is calculated according to equation 1 where:
P 480 mm/year.
C_P 10.23 mg/l.
C_R 613.8552 mg/l. average corrected Cl

R = 8.00 mm / year.
The mean annual recharge value can be considered **8 mm per year**.

Estimation of Aquifer Recharge and Vertical Water Movement using Deuterium Profile at S-3:

The previous argument applied in S-2 can be applied for S-3.

The sequence of the deuterium peaks from the beginning of the core excluding the uppermost 1.5 meters until reaching the water table takes about 9 deuterium peaks (years) to cover the vertical distance of 16 meters. Therefore the average vertical water movement velocity is about 1.77 meter per year. If we assumed that the average moisture content through out the core is 6% like in the previous core at S-2 and that the actual moisture released from sand particles and moving downward to recharge the aquifer is about 4%. Using equation 3 the calculated aquifer recharge rate will therefore be around 106.2 mm per year.

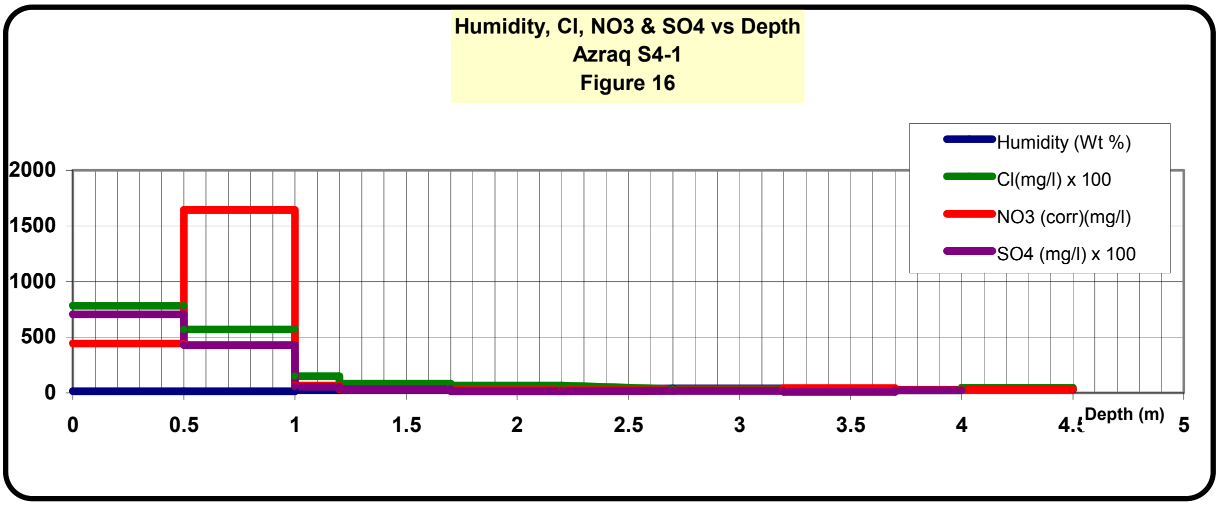
Site 4 Azraq:

In Azraq area the analytical results will be illustrated without interpretation due to:

- The relatively short time dedicated to data collection and compilation (the drilling was completed in 6 September 1999).
- The chemical analysis and lithology description showed horizons of salt deposits which interfered with the conventional interpretation of chloride results and recharge calculation.
- Deuterium was not analyzed due to unforeseen circumstances therefore soil samples were kept for future analysis.

Site (S4-1):

The analytical results of the humidity, chloride, nitrate and sulfate are shown in appendix 4 - 1 and illustrated in figure 16.
The rest of the profiles are included in appendix 4 - 1



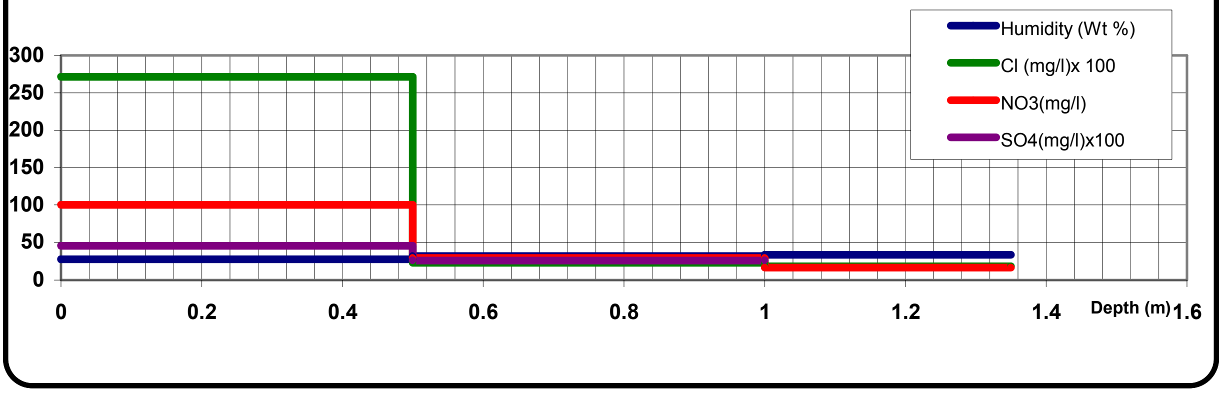
Site (S4-2):

The analytical results of the humidity, chloride, nitrate and sulfate are shown in appendix 4 - 2 and illustrated in figure 17.
The rest of the profiles are included in appendix 4 - 2

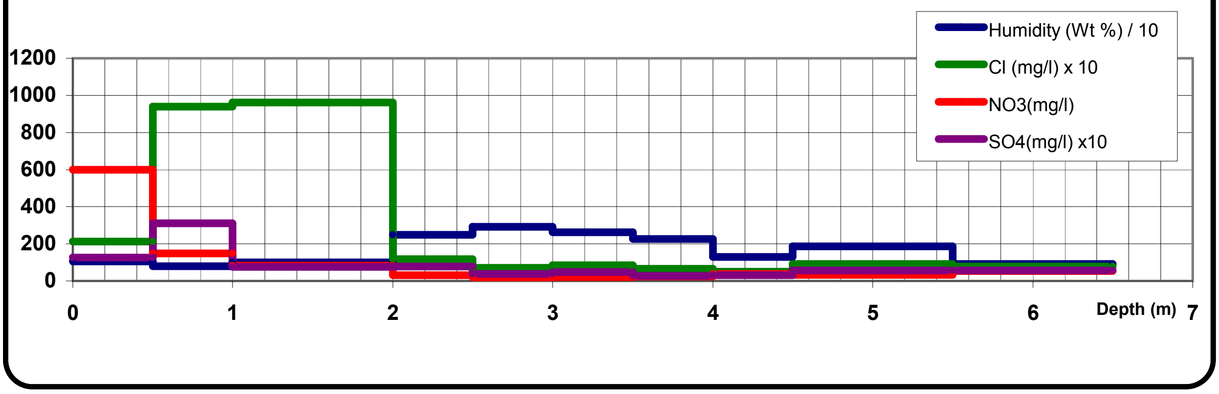
Site (S4-3):

The analytical results of the humidity, chloride, nitrate and sulfate are shown in appendix 4 - 3 and illustrated in figure 18.
The rest of the profiles are included in appendix 4 - 3

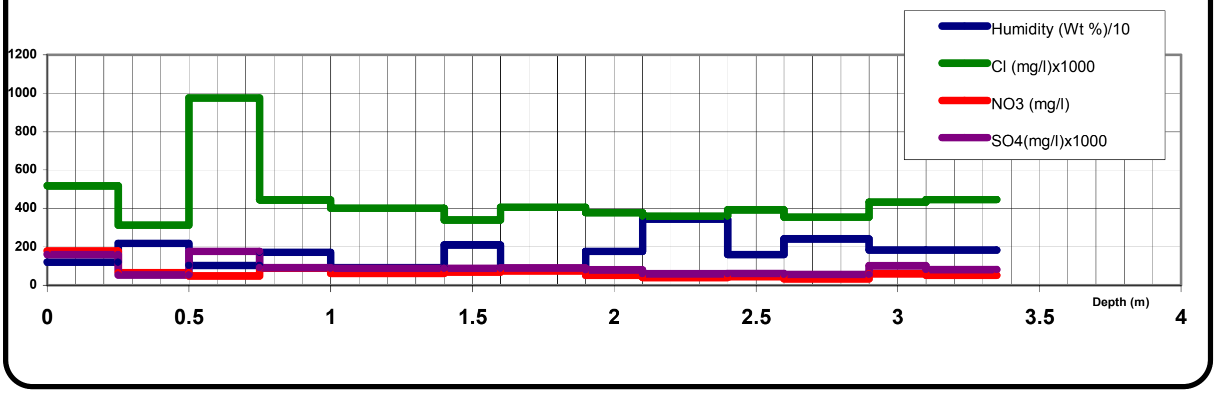
Humidity, Cl, NO3 & SO4 vs Depth
Azraq S4-2
Figure 17



Humidity, Cl, NO3 & SO4 vs Depth
Azraq S4-3
Figure 18



Humidity, Cl, NO3 & SO4 vs Depth
Azraq S4-4
Figure 19



Site (S4-4):

The analytical results of the humidity, chloride, nitrate and sulfate are shown in appendix 4 - 4 and illustrated in figure 19.
The rest of the profiles are included in appendix 4 - 4

6. Conclusions

The study conducted at Al Quwayra in southern Jordan showed that recharge if present is a result of severe infrequent storm events and that the aquifer does not receive significant direct recharge from rain.
The study in northern Jordan at Ghazza Camp showed that the average recharge that the Kurnub aquifer receives is about 28.4 mm per year. This value can be considered for the time being representative of the average recharge in Jarash sheet. The deuterium profiles presents a qualitative support of the above findings.
The recharge rate obtained site 3 is questionable. The relatively high Cl and NO3 values in soil compared to those obtained in the previous core at site S3 suggests that evaporation had occurred to the samples during a certain stage in the sample handling, most probably during the core drilling. This observation was further confirmed by Prof. Edmunds according to deuterium results.
The results of the study in Azraq will be discussed later during the coming CRP meeting entitled “Isotope Response to Dynamic Changes in Groundwater Systems due to Long – term Exploitation “ in November 1999.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. W.M. Edmunds at the British Geological Survey, Wallingford (UK), and Dr. Yurtsever at Isotope Hydrology Section, IAEA, Vienna for their guidance, advice and help during all stages of work. The authors are thankful to Eng. Moh’d Al Momani at MWI, Jordan for helping in the site selection in Azraq area and providing the needed background information. Also thanked Mr. G. Darling at BGS in Wallingford for carrying out the deuterium analyses, Mrs. R. Tuffaha, Mr. A. D. Turk and Miss. E. Hammam at WAJ Laboratory in Jordan for carrying out some of the chemical analyses.

ABBREVIATIONS

asl	Above sea level
bgl	Below ground level
BGS	British Geological Survey
WAJ	Water Authority of Jordan
MWI	Ministry of Water and Irrigation
g	Gram

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APPENDIX 1

Site 1
(*Al Quwayra area*)

Analytical results and charts

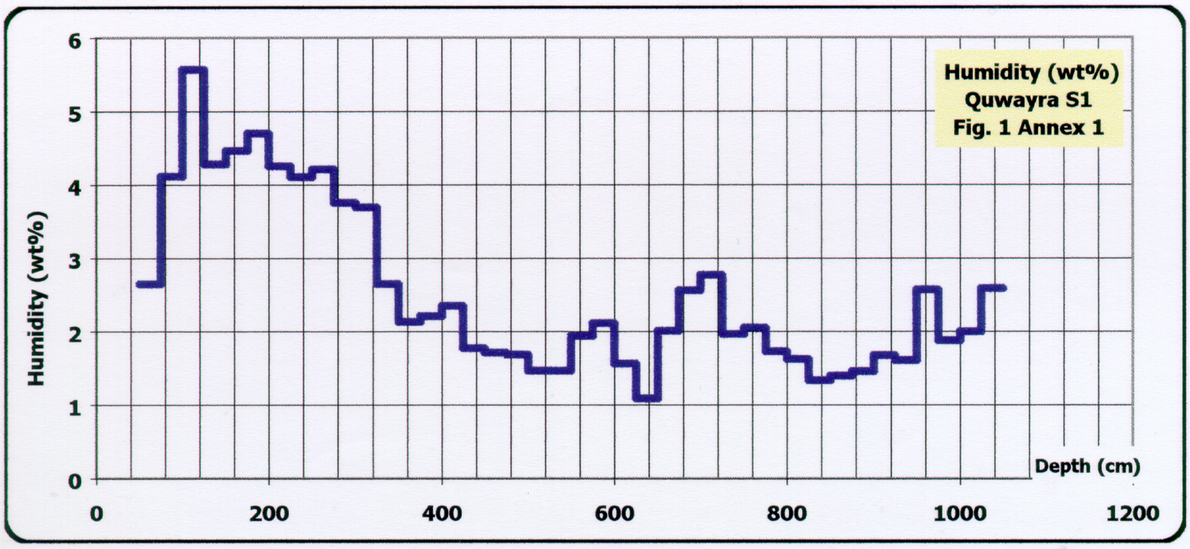
Appendix 1

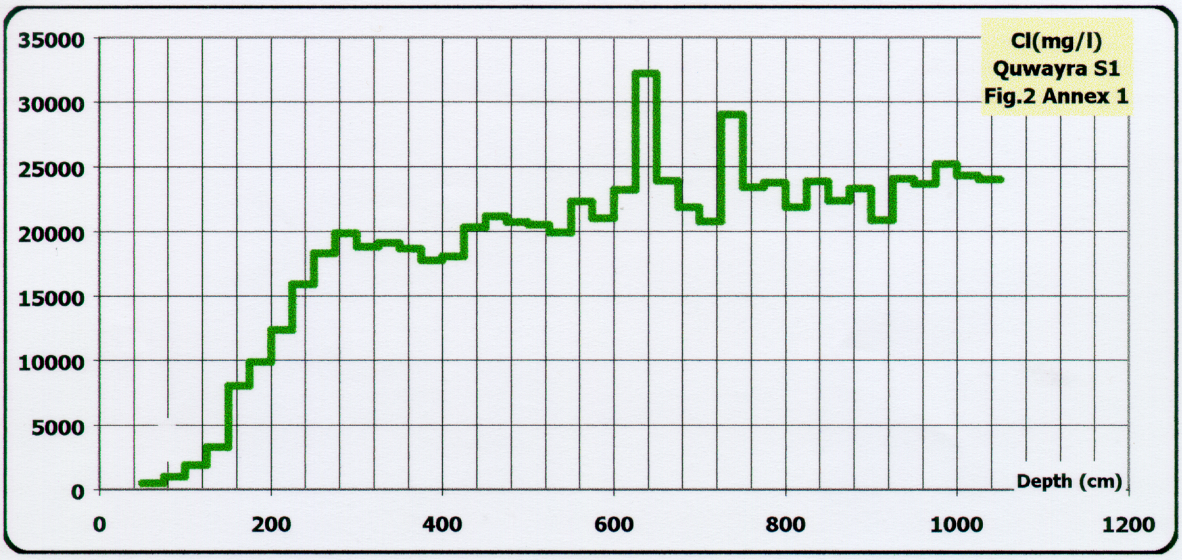
AL Quwayra S-1

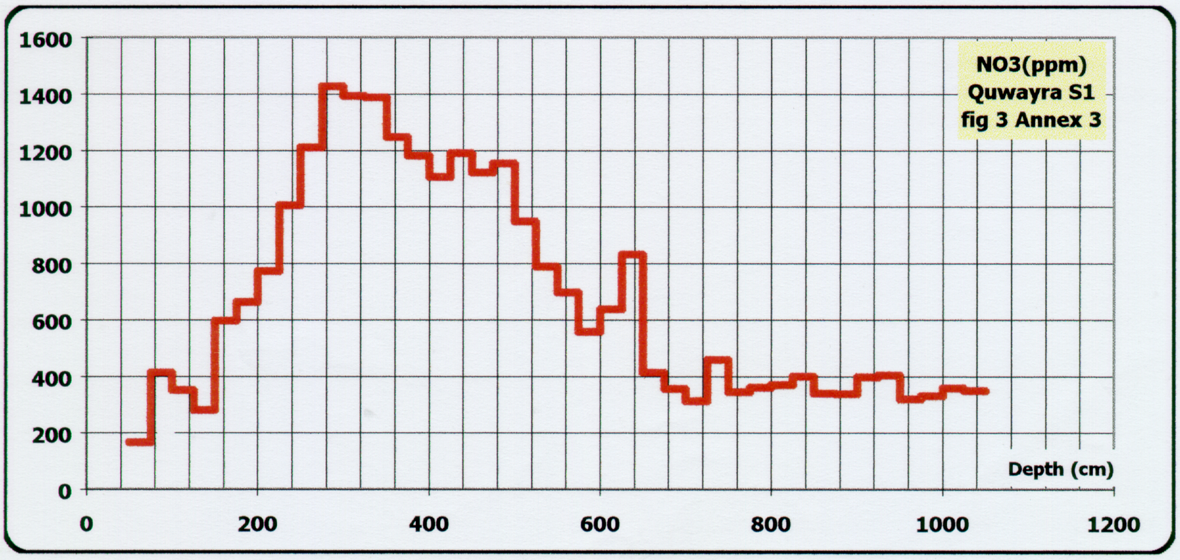
Drilling Date 23 - 28 /8/97
Depth from 50 - 1050cm
Total samples 40

Depth (cm)	Humidity (wt%)	NO3 (mg/l)	NO3 corr. (mg/l)	Cl (mg/l)	Cl corr. (mg/l)	dD ‰(BGS)
50 - 75	2.6502	7.05	166.7	20.6	487	-24
75 - 100	4.1118	26.53	413.7	64.7	1009	-12
100 - 125	5.5674	29.88	351.9	162	1908	-13
125 - 150	4.2806	18.7	280.8	219	3289	-15
150 - 175	4.4676	41.4	597.4	556	8023	-13
175 - 200	4.7046	48.24	663.5	718	9875	-11
200 - 225	4.2558	51.1	771.5	818	12350	-17
225 - 250	4.1096	64.5	1006.2	1020	15912	-17
250 - 275	4.2096	79.3	1209.6	1200	18304	-15
275 - 300	3.7576	84.15	1427.8	1170	19852	-16
300- 325	3.6936	80.75	1392.5	1090	18796	-9
325 - 350	2.6484	58.65	1387.4	808	19113	-17
350 - 375	2.1314	42.8	1247.6	639	18627	-12
375 - 400	2.2086	41.95	1181.6	630	17745	-17
400- 425	2.3544	41.75	1105.7	682	18062	-21
425 - 450	1.773	34.15	1189.8	582	20277	-5
450 -475	1.7138	31.15	1121.7	587	21138	-13
475 - 500	1.6856	31.53	1153.9	566	20713	-21
500 - 525	1.4642	22.58	947.9	488	20485	-21
525 - 550	1.464	18.78	788.5	474	19900	-20
550 - 575	1.9388	21.8	696.4	697	22267	-22
575 - 600	2.1126	19	558.6	714	20992	-7
600 - 625	1.5584	16.15	637.9	587	23187	-16
625 - 650	1.089	14.85	833.0	574	32199	-15
650 - 675	2.0096	13.35	411.9	774	23883	-23
675 - 700	2.5642	14.6	356.2	895	21837	-24
700 - 725	2.7742	13.8	312.3	916	20727	-22
725 - 750	1.969	14.55	457.9	922	29017	-18
750 - 775	2.0502	11.35	343.5	773	23395	-15
775 - 800	1.7262	10.1	361.2	664	23744	-16
800 - 825	1.6232	9.75	370.1	575	21829	-26
825 - 850	1.3306	8.65	398.7	517	23830	-22
850 - 875	1.391	7.7	339.8	506	22332	-16
875 - 900	1.4532	7.95	336.2	551	23301	-29
900 - 925	1.6732	10.75	396.2	566	20862	-21
925- 950	1.6062	10.5	402.7	626	24010	-21
950 - 975	2.5742	13.1	318.4	972	23628	-20
975 - 1000	1.8792	10.05	330.9	765	25190	-15
1000- 1025	2.0004	11.55	358.0	783	24268	-14
1025-1050	2.5844	14.4	348.7	991	23998	-10

Appendix 1


Humidity (wt%)
Quwayra S1
Fig. 1 Annex 1
Humidity (wt%)
Depth (cm)
0
1
2
3
4
5
6
0
200
400
600
800
1000
1200


Cl(mg/l)
Quwayra S1
Fig.2 Annex 1
Depth (cm)
0
5000
10000
15000
20000
25000
30000
35000
0
200
400
600
800
1000
1200


NO3(ppm)
Quwayra S1
fig 3 Annex 3
Depth (cm)
0
200
400
600
800
1000
1200
1400
1600
0
200
400
600
800
1000
1200

APPENDIX 2

Sites 2

(*Ghazza Camp, West of Jarash*)

Chloride in rainwater (Ras-Muneef and Baqa Stations)

Analytical results and charts

Appendix 2

Cl content in rain water in Ras-Muneef and Baqa Stations

SOURCES	COLL.DATE	Cl(meq/l)	Cl(mg/l)
BAQA RAIN	Mar 89	0.15	5.31795
BAQA RAIN	Nov. 91	0.15	5.31795
BAQA RAIN	Jan 92	0.15	5.31795
BAQA RAIN	Feb 92	0.25	8.86325
BAQA RAIN	Feb94	0.26	9.21778
BAQA RAIN	Mar 94	0.39	13.82667
BAQA RAIN	Nov 94	0.25	8.86325
BAQA RAIN	Dec 92	0.25	8.86325
BAQA RAIN	Nov 92	0.41	14.53573
BAQA RAIN	Mar 92	0.81	28.71693
BAQA RAIN	Jan 94	0.21	7.44513
BAQA RAIN	Feb 93	0.27	9.57231

Average	10.48818

S-2

P	480	mm/year.
CP	10.23	mg/l.
CR1	173.21	mg/l.
CR2	133.8	mg/l (Excluding the Cl peaks)
R1	28.35	mm/year.
R2	36.70	mm/year.

SOURCES	COLL.DATE	Cl(meq/l)	Cl(mg/l)
Ras Muneef	Feb 92	0.4	14.1812
Ras Muneef	Jan 94	0.21	7.44513
Ras Muneef	Feb 94	0.27	9.57231
Ras Muneef	Dec 91	0.49	17.37197
Ras Muneef	Nov + Dec 92	0.25	8.86325
Ras Muneef	Jan 92	0.29	10.28137
Ras Muneef	Nov 91	0.25	8.86325
Ras Muneef	Mar 91	0.31	10.99043
Ras Muneef	Mar 94	0.21	7.44513
Ras Muneef	Nov 94	0.16	5.67248

Average	10.06865

S-3

CR1	613.86	mg/l. average corrected Cl
CR2	396.92	mg/l (Excluding the Cl peaks)
R1	8.00	mm/year.
R2	12.37	mm/year.

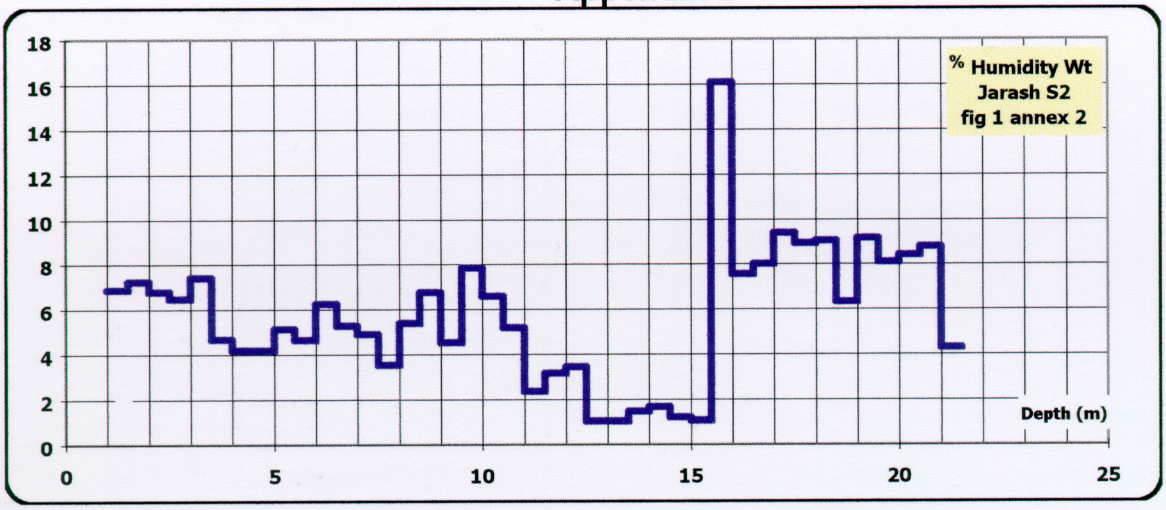
Appendix 2

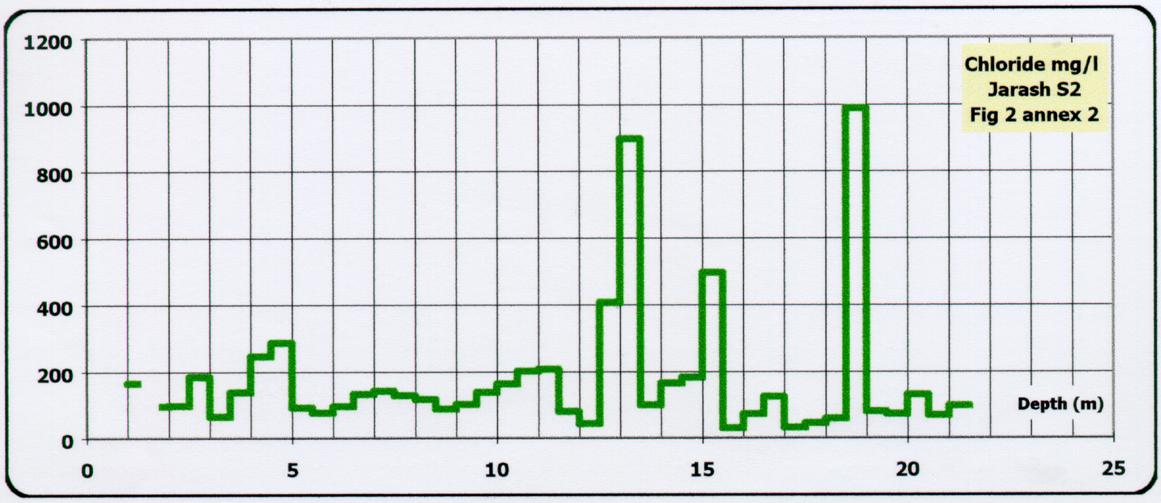
Ghazza camp (Jarash) S2

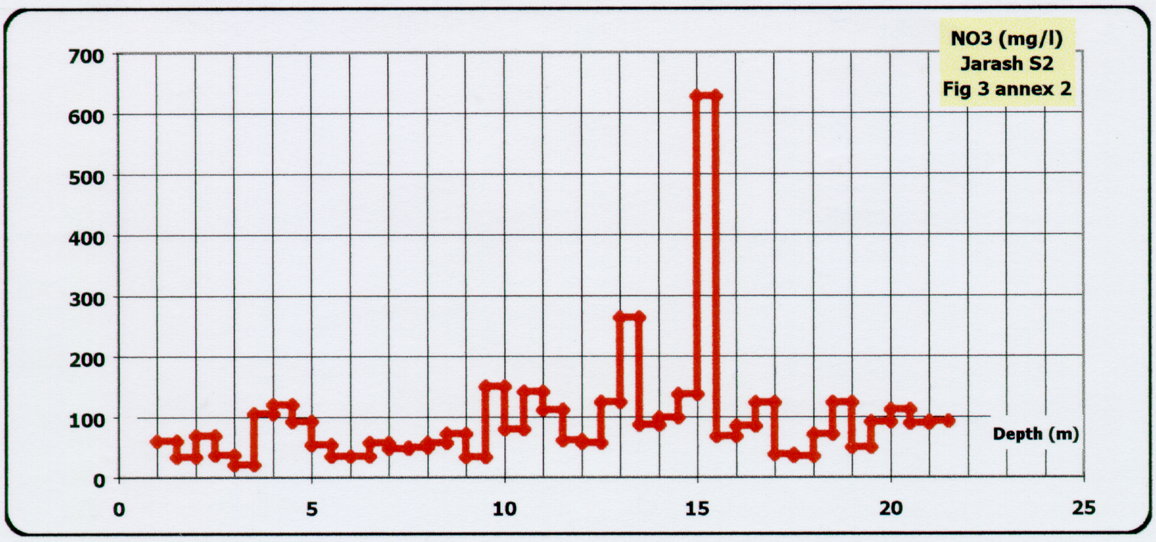
Drilling Date	**Nov-97**
Depth from	**1 - 21.5 m**
Total samples	**41**

Sample No.	Depth(m)	Wt %	Cl (mg/l)	Cl(corr.) (mg/l)	NO3 (mg/l)	NO3 (corr)(mg/l)	dD‰ (vs VSMOW)
1	1 - 1.5	6.856	16.800	163.825	6.235	60.800	-58
2	1.5 - 2	7.254	10.300	95.492	3.630	33.654	-56
3	2 - 2.5	6.796	9.900	97.302	7.035	69.143	-53
4	2.5 - 3	6.460	17.900	184.159	3.625	37.295	1
5	3 - 3.5	7.408	7.100	64.609	2.280	20.748	-61
6	3.5 - 4	4.651	9.900	137.603	7.600	105.635	-37
7	4 - 4.5	4.168	15.970	245.864	7.765	119.545	-46
8	4.5 - 5	4.190	18.700	286.506	6.040	92.540	-55
9	5 - 5.5	5.113	7.100	90.424	4.230	53.872	x
10	5.5 - 6	4.627	5.330	74.446	2.545	35.547	-27
11	6 - 6.5	6.244	8.870	94.101	3.315	35.169	-50
12	6.5 - 7	5.272	10.650	131.852	4.635	57.383	-44
13	7 - 7.5	4.889	10.700	142.010	3.570	47.381	-45
14	7.5 - 8	3.517	7.100	128.212	2.740	49.479	-54
15	8 - 8.5	5.379	9.570	116.326	4.745	57.677	-47
16	8.5 - 9	6.760	8.870	87.600	7.325	72.342	14
17	9 - 9.5	4.532	7.100	101.107	2.420	34.462	0
18	9.5 - 10	7.843	15.970	138.149	17.330	149.914	-73
19	10 - 10.5	6.572	15.970	161.779	7.895	79.978	-29
20	10.5 - 11	5.168	15.970	201.387	11.205	141.299	-68
21	11 - 11.5	2.360	7.810	206.336	4.215	111.358	-30
22	11.5 - 12	3.148	3.950	79.245	3.095	62.092	43
23	12 - 12.5	3.424	2.280	42.236	3.080	57.055	12
24	12.5 - 13	1.042	6.910	404.951	2.115	123.947	x
25	13 - 13.5	1.034	15.200	897.212	4.470	263.851	-60
26	13.5 - 14	1.446	2.330	99.010	2.045	86.900	-7
27	14 - 14.5	1.658	4.440	165.116	2.660	98.921	x
28	14.5 - 15	1.192	3.550	182.241	2.660	136.553	52
29	15 - 15.5	1.068	8.660	495.268	10.980	627.949	x
30	15.5 - 16	16.075	6.220	29.437	14.305	67.700	9
31	16 - 16.5	7.546	7.910	70.804	9.455	84.634	x
32	16.5 - 17	8.022	14.500	122.952	14.530	123.206	84
33	17 - 17.5	9.384	4.190	30.980	5.160	38.152	-40
34	17.5 - 18	8.920	5.710	44.118	4.565	35.271	-3
35	18 - 18.5	9.031	7.610	58.171	9.325	71.281	82
36	18.5 - 19	6.339	94.300	986.926	11.810	123.601	x
37	19 - 19.5	9.166	10.600	79.987	6.595	49.765	x
38	19.5 - 20	8.104	8.430	70.844	10.845	91.139	x
39	20 - 20.5	8.402	15.900	129.444	13.730	111.778	-37
40	20.5 - 21	8.776	8.520	66.770	11.320	88.713	76
41	21 - 21.5	4.285	6.440	96.617	6.170	92.566	78

Appendix 2


% Humidity Wt
Jarash S2
fig 1 annex 2
Depth (m)
0
2
4
6
8
10
12
14
16
18
0
5
10
15
20
25


Chloride mg/l
Jarash S2
Fig 2 annex 2
Depth (m)
0
200
400
600
800
1000
1200
0
5
10
15
20
25


NO3 (mg/l)
Jarash S2
Fig 3 annex 2
Depth (m)
0
100
200
300
400
500
600
700
0
5
10
15
20
25

APPENDIX 3

Sites 3
(*Ghazza Camp, West of Jarash*)

Analytical results and charts

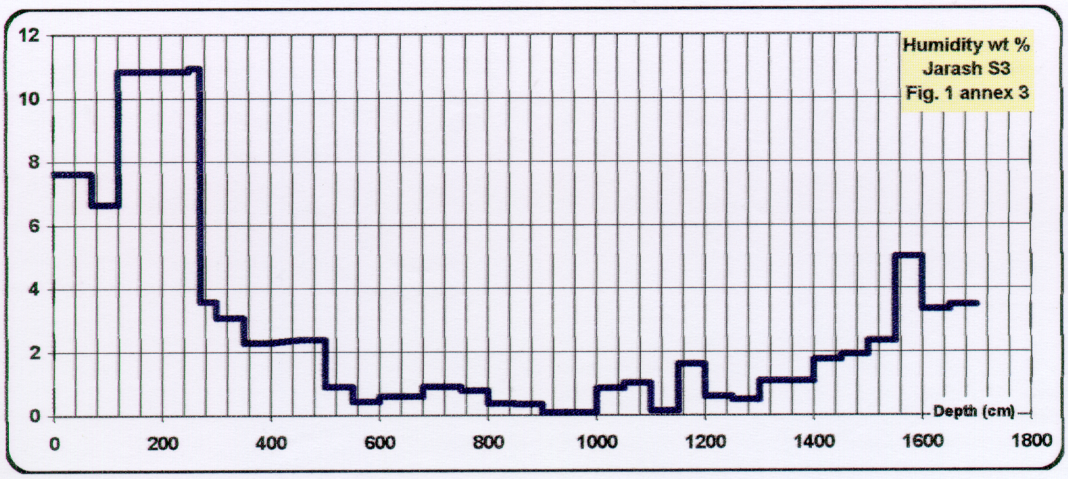
Appendix 3

Ghazza camp (Jarash) S3

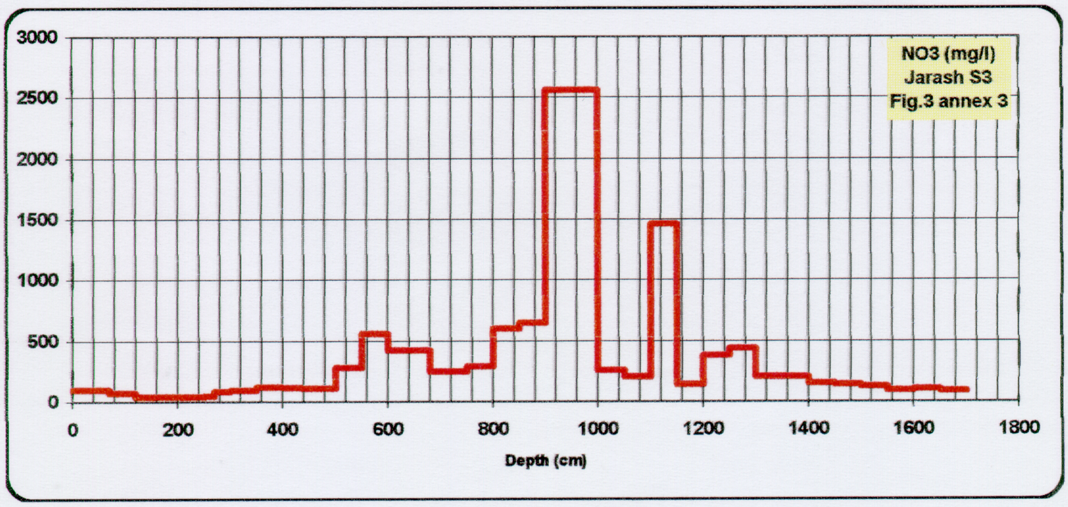
Drilling Date	**October**	**98**
Depth from	**0 - 17 m**	
Total samples	**30**	

Depth(m)	Humidity Wt %	Cl (mg/l)	Cl(corr.) (mg/l)	NO3 (mg/l)	NO3 (corr)(mg/l)	dD‰ (vs VSMOW)
0-70	7.62	27.70	245.81	11.20	99.39	-36
70-120	6.64	15.25	153.05	7.65	76.78	-18
120-250	10.82	7.29	47.72	6.28	41.10	-25
250-270	10.92	18.99	123.33	7.11	46.18	-37
270-300	3.58	6.99	124.14	4.70	83.47	-11
300-350	3.06	6.03	124.27	4.52	93.15	-16
350-400	2.28	6.20	169.36	4.46	121.83	-22
450-500	2.38	5.58	146.25	4.27	111.92	-31
500-550	0.9	5.84	395.17	4.17	282.17	-26
550-600	0.42	6.18	889.04	3.87	556.73	-29
600-680	0.58	5.31	554.62	4.04	421.97	-16
680-750	0.9	5.27	356.60	3.72	251.72	33
750-800	0.78	5.22	406.76	3.72	289.87	13
800-850	0.36	5.17	866.84	3.56	596.89	43
850-900	0.34	5.75	1020.46	3.63	644.22	54
900-1000	0.08	5.45	4092.95	3.41	2560.91	-18
1000-1050	0.86	10.04	710.51	3.65	258.30	-7
1050-1100	1.022	7.15	426.92	3.44	205.40	30 / 35
1100-1150	0.14	7.47	3208.90	3.41	1464.84	-21
1150-1200	1.6	8.04	309.54	3.67	141.30	-21
1200-1250	0.58	8.53	890.94	3.67	383.33	1 / -3
1250-1300	0.48	8.05	1014.30	3.50	441.00	34
1300-1350	1.08	8.31	469.98	3.69	208.69	17
1350-1400	1.08	8.12	459.23	3.66	206.99	21
1400-1450	1.74	9.04	320.76	4.32	153.29	21
1450-1500	1.9	7.99	260.31	4.47	145.63	28
1500-1550	2.34	8.13	216.59	4.73	126.01	32
1550-1600	5	8.25	107.25	7.18	93.34	6
1600-1650	3.32	8.44	160.97	5.49	104.71	7
1650-1700	3.48	7.80	142.28	5.07	92.48	21

Appendix 3


Humidity wt %
Jarash S3
Fig. 1 annex 3
12
10
8
6
4
2
0
Depth (cm)
0
200
400
600
800
1000
1200
1400
1600
1800


Cl (mg/l)
Jarash S3
Fig. 2 annex 3
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
200
400
600
800
1000
1200
1400
1600
1800
Depth (cm)


NO3 (mg/l)
Jarash S3
Fig.3 annex 3
3000
2500
2000
1500
1000
500
0
0
200
400
600
800
1000
1200
1400
1600
1800
Depth (cm)

APPENDIX 4

Chloride in rainwater (Azraq Rain Station)

Appendix 4-1
Site S4-1
Azraq
Analytical results and charts

Appendix 4-2
Site S4-2
Azraq
Analytical results and charts

Appendix 4-3
Site S4-3
Azraq
Analytical results and charts

Appendix 4-4
Site S4-4
Azraq
Analytical results and charts

Appendix 4

Cl Content in rain water collected from Azraq station

Lab NO.	Coll Date	Rain amount (mm)	T (TU)	Cl (mg/l)
91-439	Oct-91			67.45
92-5	Jan-92			26.27
92-24	Feb-92			126.38
92-56	Mar-92			103.66
92-454	Nov-92	8.80		95.85
93-41	Jan-93	13.00		136.32
93-70	Feb-93		10.90	22.72
93-132	Mar-93			75.97
94-37	Dec-93			78.1
94-38	Jan-94			24.14
94-45	Mar-94			43.31
94-267	Sep-94	3.00		102.24
94-268	Nov-94	39.30	5.90	17.75
94-282	Dec-94			12.07
97-6	Dec-96	9.00		45.44
97-28	Feb-97	6.40		24.85
98-5	Jan-98	24.00	6.90	47.57
98-203	Apr-98	5.60		49.7
98-425	Feb-98	11.00	7.20	47.57
99-62	Jan-99		12.90	97.98
99-68	Jan-99	13.00		26.27
99-99	Feb-99			61.77

Average	60.60818182

Appendix 4-1

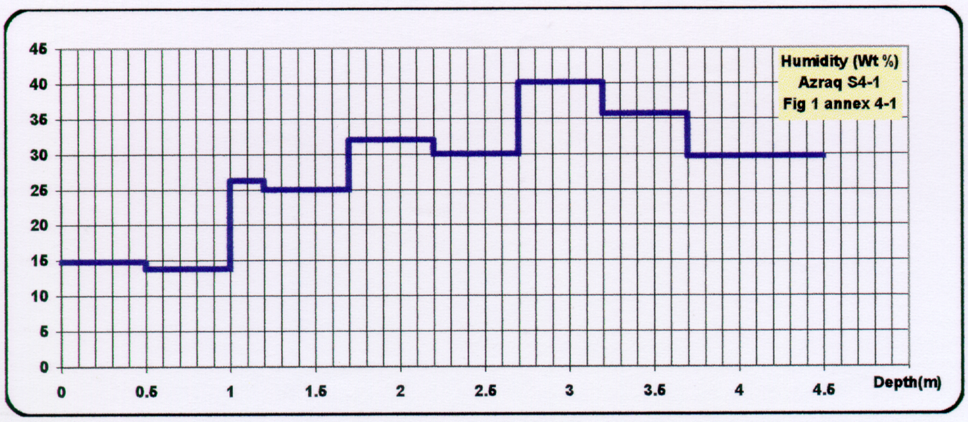
Azraq S4 -1

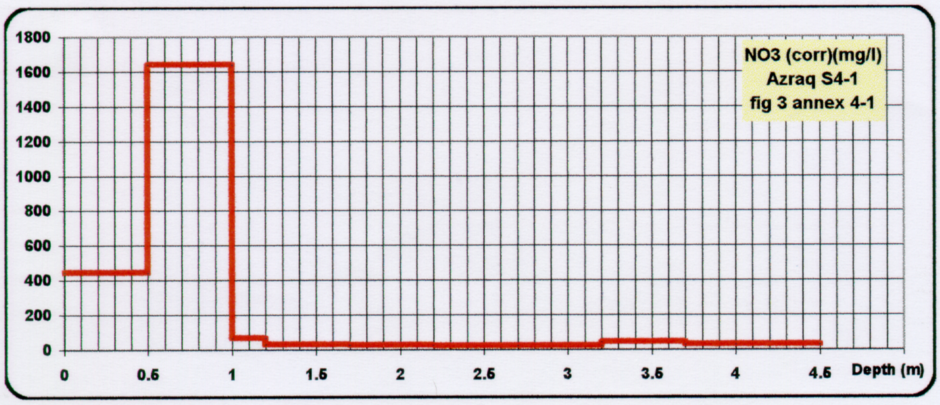
Drilling Date	1 to 6 September 1999	
Depth	7 meter	
Samples Obtained	from 0 to 4.5 meter	
Total Samples	10	at 0.5 meter intervals
Rest of Core	From 4.5 to 7 Basalt	

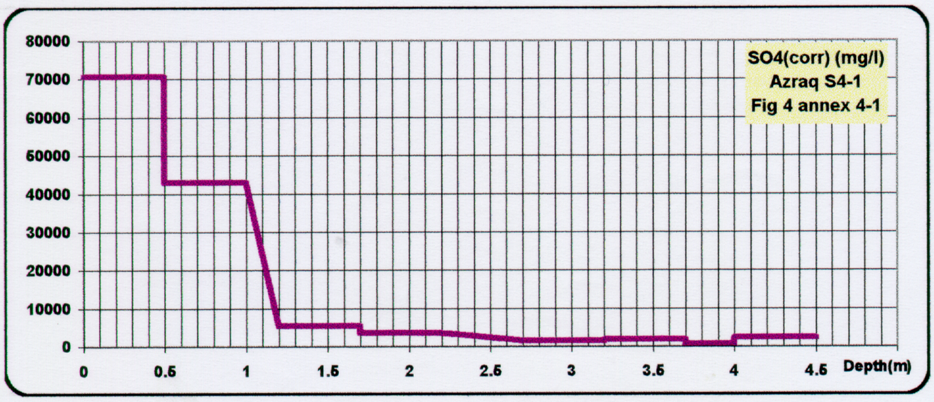
Depth(m)	Humidity (Wt %)	Cl (mg/l)	Cl(corr.) (mg/l)	NO3 (mg/l)	NO3 (corr)(mg/l)	SO4 (mg/l)	SO4(corr) (mg/l)
0.0 - 45	14.8	15507.50	78375.74	87.79	443.70	13975.00	70630.41
0.5 - 0.95	13.8	10655.00	56981.09	307.07	1642.16	8020.00	42889.57
1.0 - 1.2	26.22	4581.00	15063.84	19.89	65.40	x	
1.2 - 1.65	25	2461.50	8369.10	8.40	28.56	1593.50	5417.90
1.7 - 2.15	32	2290.25	6584.47	8.90	25.59	1241.50	3569.31
2.2 - 2.65	30	x	x	x		x	
2.7 - 3.15	40.1	1429.00	3567.15	9.28	23.17	596.00	1487.77
3.2 - 3.65	35.6	1385.50	3720.61	16.28	43.72	695.50	1867.69
3.7 - 4.0	29.64	746.22	2256.79	9.49	28.70	245.50	742.46
4.0 - 4.5	29.6	1490.25	4511.03	10.24	31.00	802.25	2428.43
Average	27.676		19936.65		259.11		16129.19

Appendix 4-1

Azraq S4- 1







Appendix 4-2

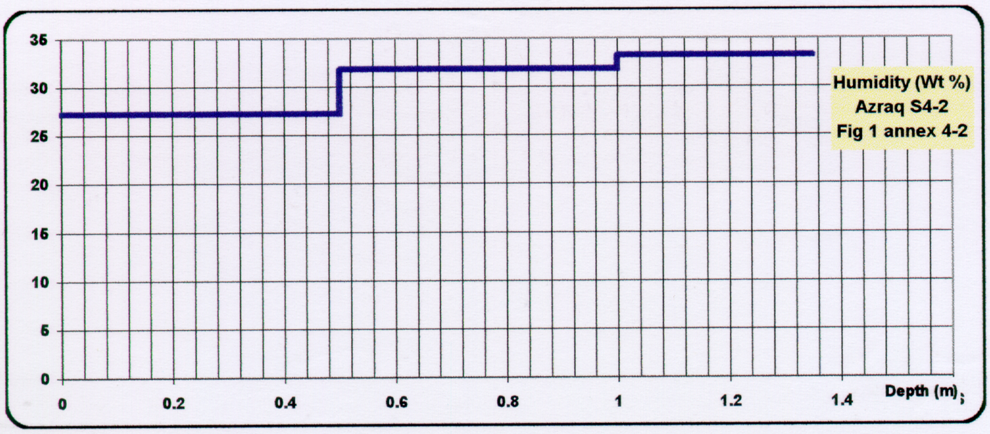
Azraq S4- 2

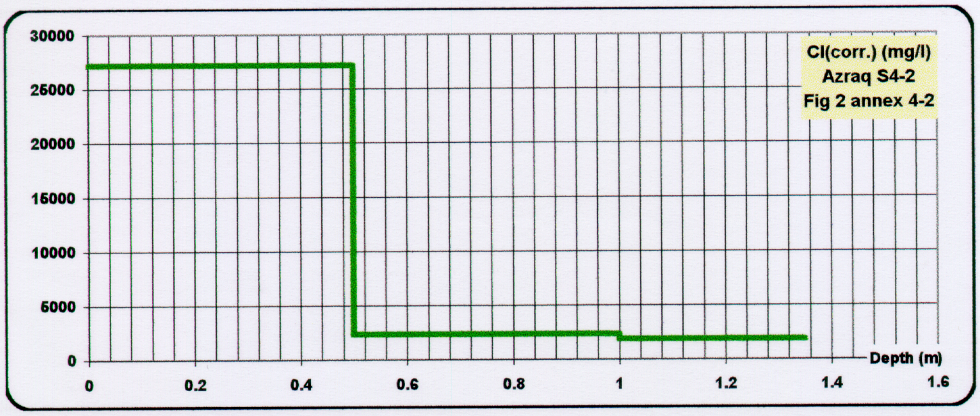
Drilling Date	1 to 6 September 1999	
Depth	7 meter	
Samples Obtained	from 0 to 1.35 meter	
Total Samples	3	at 0.5 meter intervals
Rest of Core	From 1.35 to 7 Basalt	

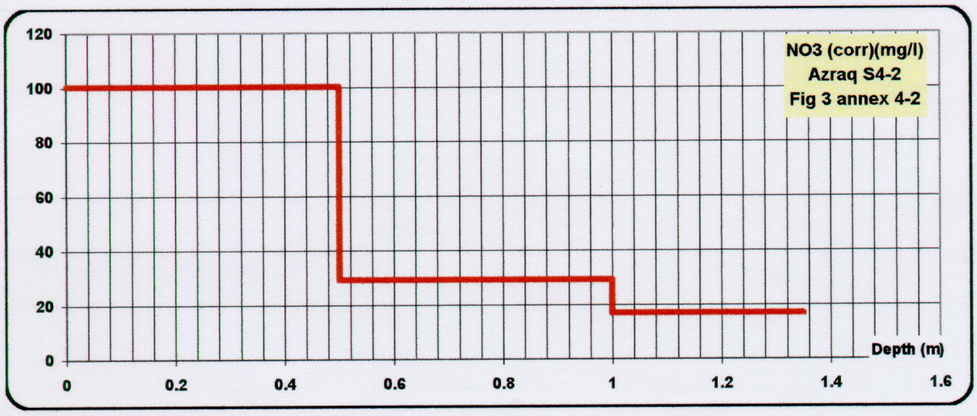
Depth(m)	Humidity (Wt %)	Cl (mg/l)	Cl(corr.) (mg/l)	NO3 (mg/l)	NO3 (corr)(mg/l)	SO4 (mg/l)	SO4(corr) (mg/l)
0.0 - 0.45	27.2	8461.12	27125.36	31.24	100.15	1415.9	4539.21
0.5 - 1.00	31.8	795.3	2295.87	10.1	29.16	905.8	2614.86
1.00 - 1.35	33.2	660.5	1854.17	5.98	16.79	x	

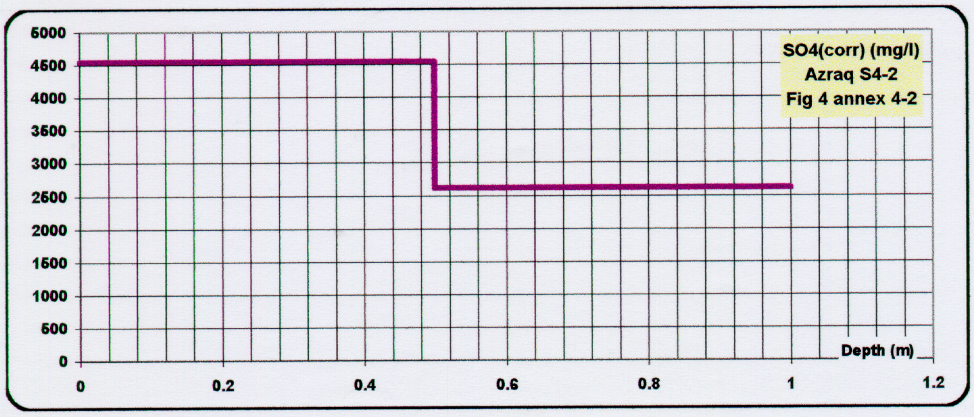
Appendix 4-2

Azraq S4- 2









Appendix 4-3

Azraq S4 -3

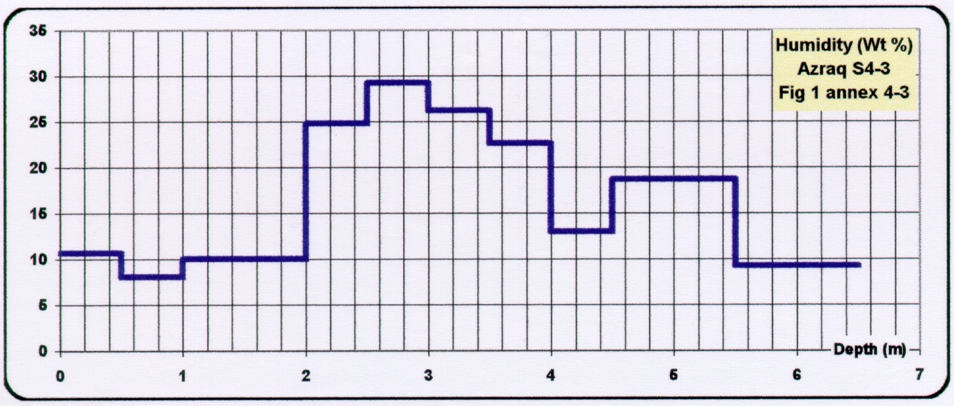
Drilling Date	1 to 6 September 1999
Depth	6.5 meter
Samples Obtained	from 0 to 4.5 meter
Total Samples	10 at 0.5 meter intervals

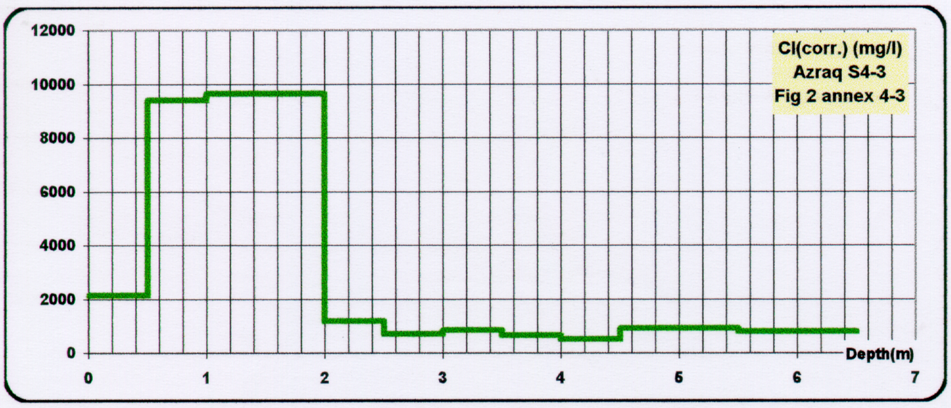
Depth(m)	Humidity (Wt %)	Cl (mg/l)	Cl(corr.) (mg/l)	NO3 (mg/l)	NO3 (corr)(mg/l)	SO4 (mg/l)	SO4(corr) (mg/l)
0.00 - 0.45	10.6	318.8	2123.33	89.92	598.90	190.35	1267.80
0.5 - 1.00	8	1105.1	9393.35	17.39	147.82	365.4	3105.90
1.00 - 2.00	10	1374.3	9620.10	11.93	83.51	107.4	751.80
2.00 - 2.50	24.8	340.9	1165.66	9.19	31.42	224.9	769.01
2.50 - 3.00	29.2	230.37	703.73	6.35	19.40	125.23	382.55
3.00 - 3.50	26.2	256.58	844.17	6.28	20.66	144.4	475.09
3.50 - 4.00	22.62	180.25	658.37	6.82	24.91	76.29	278.65
4.00 - 4.50	12.94	89.25	503.08	6.84	38.56	56.03	315.83
4.50 - 5.50	18.68	216.41	911.52	7.77	32.73	135.58	571.06
5.5 - 6.5	9.2	104.39	785.19	7.08	53.25	75.66	569.09

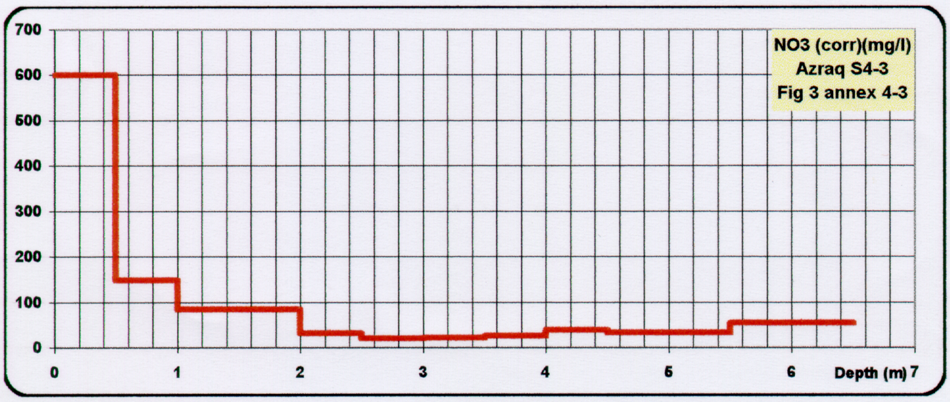
Average	17.224	2670.849837	105.115651	848.6791071

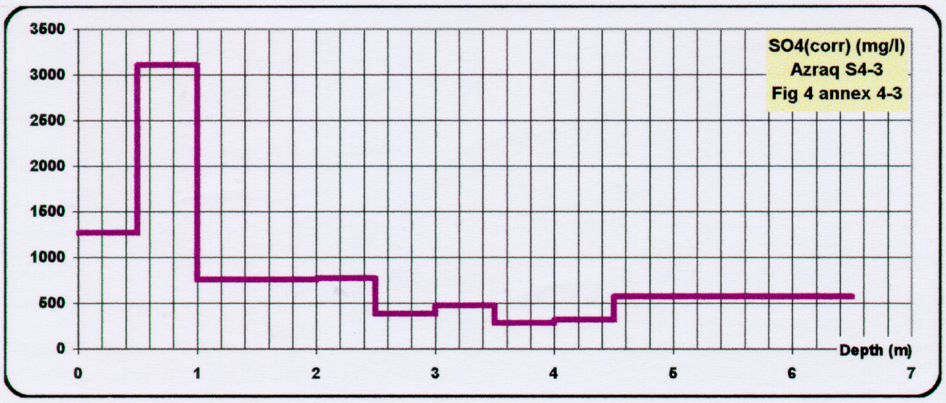
Appendix 4-3

Azraq S-3









STRATIGRAPHY OF JORDAN

ERA	PERIOD	GROUP	FORMATION	SYMBOL	AQUIFER	AQUICLUDE	HYDRAULIC
	Quaternary	Holocene	Mantle Rocks	R	Gravel,Sand	Marl,Silt Gypsum	Shallow
Cainozoic							Aquifer
		Pleistocene	Volcanics	Ba	Basalt		
							Hydraulic
			Sirhan-Dana	Si-Da	Limest.,Gravl.	Marl,Silt	
	Tertiary			Ba	Basalt		Complex
			Wadi Shallala	B5	Limestone		
			Rijam	B4	Chert		
		Belqa	Muwaqqar	B3		Marl,Chert	
			Amman	A7-B2	Chert,Limest.		Middle
	Upper		Wadi Ghudran	A7-B2	Chert,Limest.		
			Wadi Sir	A7-B2	Chert,Limest.		Aquifer
			Shueib	A1-A6	Limestone		
	Cretaceous	Ajlun	Hummar	A1-A6	Dolomite	Marl	Hydraulic
			Fuheis	A1-A6	Sandstone		
Mesozoic			Naur	A1-A6	Lst.Dolo.Sdst.		Complex
	Lower		Subeihi	K	Sandstone,		
		Kurnub			Dolomite		Deep
	Cretaceous		Aarda	K	Sandstone,		
					Dolomite		Sandstone
	Jurassic		Azab	Z	Sandstone,		
		Zerqa			Dolomite		Hydraulic
	Trias		Main	Z	Sandstone,		
					Dolomite		Complex
	Permian						
Paleozoic	to	Khreim		Kh	Sdst.,Siltst.	Shale	
	Silurian						
	Ordovician						
			Disi	D	Sdst.,Quartzite		
	Cambriam						
Precambrian		Basement Complex		G		Granite	

Source: National Water Master Plan of Jordan, BGR/NRA/GTZ, 1977

Appendix 4-4

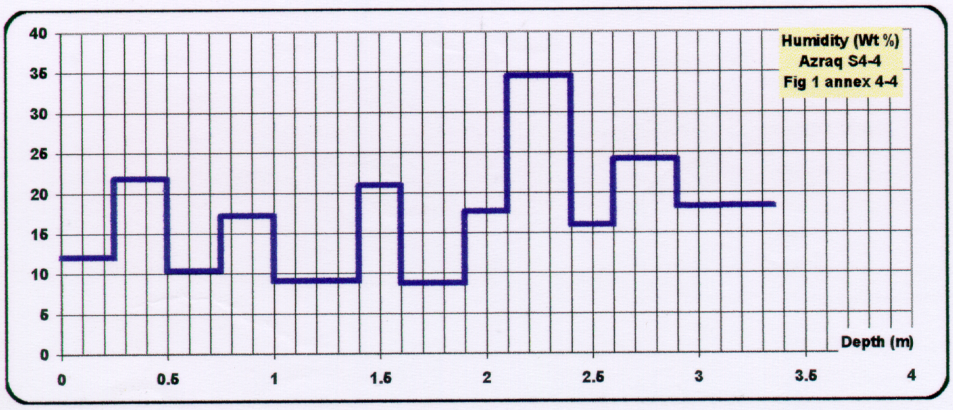
Azraq S4 -4

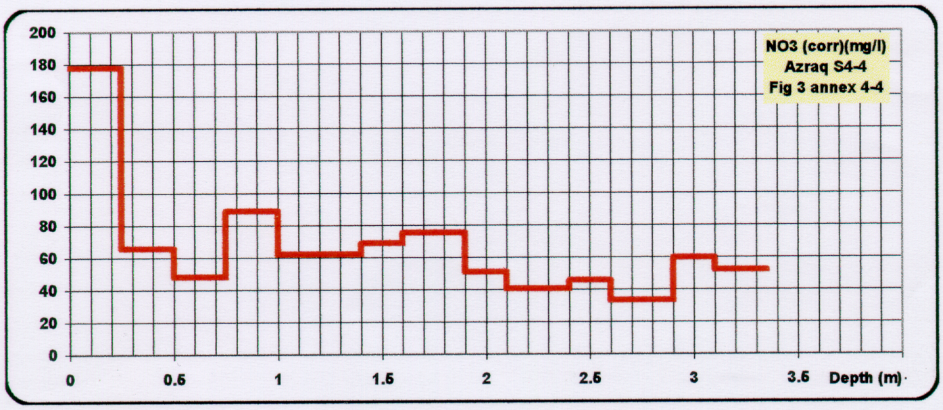
Drilling Date	1 to 6 September 1999	
Depth	11 meter	water was encountered at 5.5 meter bgl
Samples Obtained	from 0 to 3.35 meter	
Total Samples	13	at 0.25 meter intervals
Rest of Core	From 3.35 to 11 Basalt	
	The last 5 meters are drilled in the saturated zone	

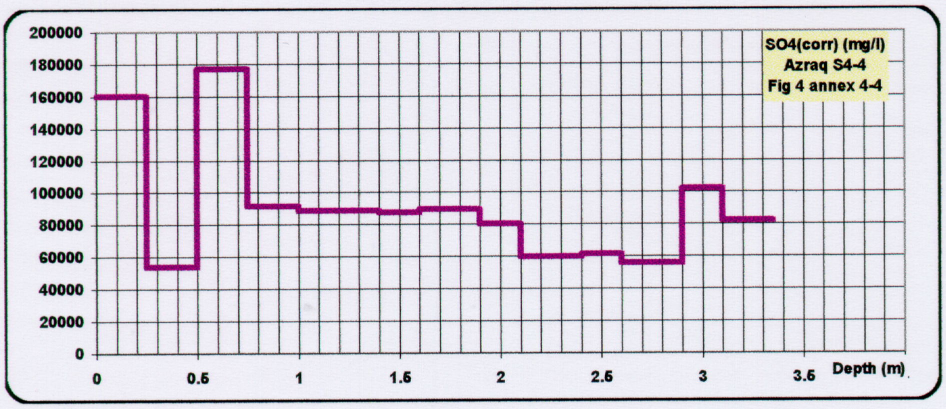
Depth(m)	Humidity (Wt %)	Cl (mg/l)	Cl(corr.) (mg/l)	NO3 (mg/l)	NO3 (corr)(mg/l)	SO4 (mg/l)	SO4(corr) (mg/l)
0.0 -0.25	12.04	86265	516157.03	29.7	177.71	26735	159965.90
0.25 - 0.5	21.84	83570	313157.91	17.45	65.39	14287	53537.00
0.50 - 0.75	10.32	143180	975621.86	7.05	48.04	25945	176788.02
0.75 - 1.00	17.14	98715	444275.09	19.68	88.57	20325	91474.36
1.00 - 1.30	9.06	52607	400997.73	8.1	61.74	11610	88497.42
1.40 - 1.60	20.92	87695	339210.30	17.78	68.77	22640	87573.08
1.60 - 1.85	8.7	51270	404856.21	9.5	75.02	11310	89310.00
1.90 - 2.10	17.6	85545	377175.68	11.51	50.75	18225	80355.68
2.10 - 2.35	34.46	131000	359090.54	14.65	40.16	21827	59831.06
2.40 - 2.60	15.96	82385	392103.05	9.53	45.36	12912	61453.35
2.60 - 2.85	24.12	101480	353917.81	9.52	33.20	16025	55888.18
2.90 - 3.10	18.2	100605	432269.84	13.86	59.55	23760	102089.67
3.10 - 3.35	18.3	104020	445069.18	12.09	51.73	19170	82022.46
Average	17.58923077		442607.8629		66.61436396		91445.09119

Appendix 4-4

Azraq S4-4







Isotopes based assessment of groundwater renewal and related anthropogenic effects in water scarce areas: Sand dunes study in Qasim area, Saudi Arabia

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Riyadh, Saudi Arabia

Abstract. The investigation of recharge in the sand dune, Qasim, Saudi Arabia, with the help of chloride concentration and isotope content has revealed inconsistent pattern and less homogeneity. Monotonic chloride concentration and isotope content was the result of seasonal recharge occurrence in the study area. In addition, applying chloride mass-balance method, recharge rate calculation in the sand dune site, Qasim, Saudi Arabia, was made. The results (1.80 and 1.84mmy^{-1} – dune site) estimated during this project using this method was a long way below the recharge rates (30mmy^{-1}, 13.4mmy^{-1} in the dune site and 5mmy^{-1} in the swale site) obtained with the application of tritium method in the previous years (1994 and 1996). 1.80 and 1.84mmy^{-1} was for CRP-Saud-9405 project and was calculated 1997 and 1998 respectively. The reason for the lower recharge rate with the application of chloride mass-balance method could be the source of chloride input and high evaporation, which causes accumulation of chloride salts in the area.

Introduction

The project forms part of the International CRP projects of IAEA. Its number is SAU-9405 and entitled "**Isotopes Based Assessment of Groundwater Renewal and Related Anthropogenic Effects in Water Scarce Areas: Sand Dune Study in Qassim Area, Saudi Arabia".** The project was formally commenced in April 1997 where drilling and coring some boreholes were conducted in Qassim region, Saudi Arabia.

The objectives of the project was to assess and ascertain the movement and renewal of groundwater in sand dunes of Qassim region and estimate the annual volume of recharge to the sand dune aquifers in the region, using stable isotope content and chloride concentration in the soil samples.

In the previous report (Oct. 1997), water content, water potential, deuterium and chloride results were presented. The rate of recharge and water movement was also presented. The rate of recharge result calculated in 1997 in the dune site using chloride mass-balance method was about 1.80mmy^{-1}[1]. The value was much far below the previous results of recharge rate (30mmy^{-1}, 13.4mmy^{-1} in the dune site and 5mmy^{-1} in the swale site) presented in the previous studies for the area in 1994 and 1996 [2,3]. The latter results were obtained by using tritium method. Comments and comparison of the two methods (tritium peak and chloride mass-balance) in terms of application for recharge calculation was made in the previous report. The influence of the nature for both methods was discussed. The purpose is to present a comprehensive and conclusive result of the project in this paper.

1. Materials and methods

1.1. Site location

The field sampling was carried out at the KACST field station located at Qassim (320-km northwest of Riyadh). A portable Global Positioning System (GPS) unit was used to "map" the position of all sites in relation to each other and to the boundaries of the KACST field station (Fig. 1). The intention of the trip was to sample at the dune where previous work has been carried out. Upon arrival it was found that access to the dune site was not possible due to roadwork, and another site ~1-km southeast of the previous dune sites was selected. The hole at this site was designated CRP-1.

Climate

The precipitation is very scarce in this part of the Kingdom of Saudi Arabia and attains 110mm annually and some times less than that value. Temperature variation throughout the year is the characteristic of the study area. The average precipitation (133mm) in the study area for last 6 years is higher than the annual average precipitation in Kingdom of Saudi Arabia. Table 1 shows the results of rainfall for the last 6 years. The precipitation of some months is missing from the table, indicating no precipitation occurred during that month or not recorded.

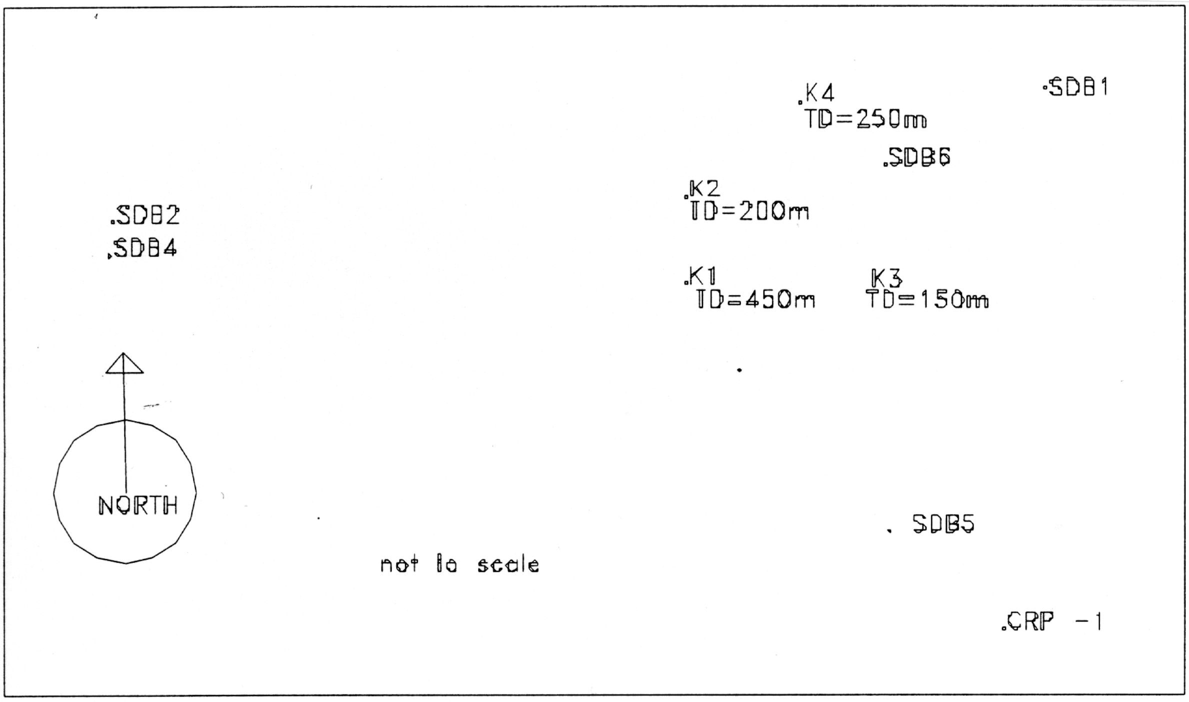

FIG. 1. Sand dune Augering sites in Oassim area (Oct. 95), KACSI research station.

Field work

Drilling at the dune site (CRP-1) commenced at ~7.00am on April 16, 1997 with Al-Sagaby, Allafouza, Moallim and two locally hired laborers in attendance. As only Al-Sagaby and Moallim had used the sand-drill previously, progress was slow and it took nearly the whole day to drill the hole. Rainfall had fallen on the previous days and the surface soils were relatively moist. Three soil samples for the interval 0.3-1.15 of the upper surface were taken prior auguring. To prevent collapse of the upper levels of the hole a 2-m length of PVC tube was inserted in the ground. Coring with sand-drill commenced and was generally carried out at 1-m intervals. When soil collapsed into the hole between samples, only core from the lower portion of the core barrel was used. Coring was carried out successfully until a hard gravely layer was reached at 17.10 m and no further drilling was possible. For all sampling intervals soil was placed in both a 1-L airtight glass jar and 0.75-L airtight steel can. Another trip was attempted last May 1999 with new drilling machine called Power Probe Auger. The new instrument was mounted on a small truck and can be easily operated by four persons. The power probe soil sampler has a capability of preventing soil contamination and collecting undisturbed sample. This last trip with this instrument was not successful due to certain constraints.

Table 1. Rainfall data (mm) for last six years from the study area

(data were collected from kacst and the agricultural research center meteorological stations in qassim)

Month	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**Average**
January	-	16.6	3.8	38	4	22.8	
February	-	1.0	36.7	5.3	0.0	1.0	
March	-	9.8	57.2	13.5	59.9	52.6	
April	-	46.6	34.2	29.9	4.6	10.7	
May	-	7.6	1.2	2.8	2.0	13.0	
June	-	-	0	0	0	-	
July	-	-	0	0	0	-	
August	-	-	0	0	0	-	
September	-	-	0	0	0	-	
October	4.8	15.7	-	-	-	-	
November	0.8	26.7	2.8	4.0	107	-	
December	1.6	21.6	118	0.8	16.1	-	
Total =	**7.2**	**146**	**254**	**94.3**	**193.6**	**100.1**	**133**

Some separate field trips were made for rainwater collection from some stations in the region, giving priority the study area. This has helped the knowledge of chloride input and its magnitude in rainwater. The updated rainfall data available is up to May 1998 (the end of the rainy season).

1. 2. Sample analyses

The following analyses were made at the KACST laboratory: gravimetric water content (0_g), matric suction and $[Cl^-]$ in the soil water. In addition, water from the soil was azeotropically distilled using the methods described in the previous report [2]. The chloride analyses were carried out by titration using a digital burette capable of dispensing aliquots of $AgNO_3$ as small as 0.03 ml.

Azeotropic distillations were carried out using ~500 g aliquots of soil in 1 L flasks and were heated for 75 (wet samples) to 90 minutes (dry samples). Yields of about 100% were obtained in all cases. Up to two aliquots of soil per sample (approximately the whole sample was used) were distilled to obtain maximum water available in the sample for stable isotope and tritium analyses (at least 15 ml). The water extracted by azeotropic distillation was sent to the British Geological Survey (BGS) laboratory in Wallingford for oxygen-18, deuterium and tritium analyses, but Deuterium result was received.

2. Results and discussion

2.1. Water content and matric suction

The water content and matric suction profile for CRP-1 are shown in Figure 2. There is an evidence of slightly wetter conditions, in the upper 2 m of the profile, presumably due to residual rainfall from storms during the previous years which was much wetter (average ~ 133mmy^{-1}) than the average rainfall (~110mmy^{-1}) in the Kingdom of Saudi Arabia. Collected rainfall data during the previous years is shown in Table 1. The water contents are relatively low (< 0.010g/g) in the depth between 2.7 and 5.6m, as are the matric suctions (< 70 kPa). The highest metric suction peak is located at depth of 6.5m below the surface, representing dry period. In between 13 and 17m, there is a peak in water content of up to 1.5%, presumably due to increased clay content (high capacity of water retention) as the matric suction in this zone decreased. The profile, generally, shows a shift of water content towards the deeper parts of hole (fig. 2.). Descending below 9.7m, there is a monotonic increase in water content. Moreover, the water content in the profile shows that the total water stored in the profile is 300mm (fig. 3.).

2.2. Chloride

The Chloride concentration for CRP-1 is shown in figure 4. Concentration increases monotonically from values of about 3169 mg L^{-1} near the surface to about 20000 mg L^{-1} at about 16m. A distinct peak with a maximum value of about 10,000 mgL^{-1} is found at about 9.2m below the surface.The contrasting zones of low and high chloride concentrations are suggestive of distinct intervals of dry and wet season. This can be further illustrated by plotting cumulative chloride versus depth for the entire profile (Fig. 4). The differing slopes could also be a result of changes in the chloride input to the profile (by rainfall or dryfall) or some combination of these and changes in recharge regime.

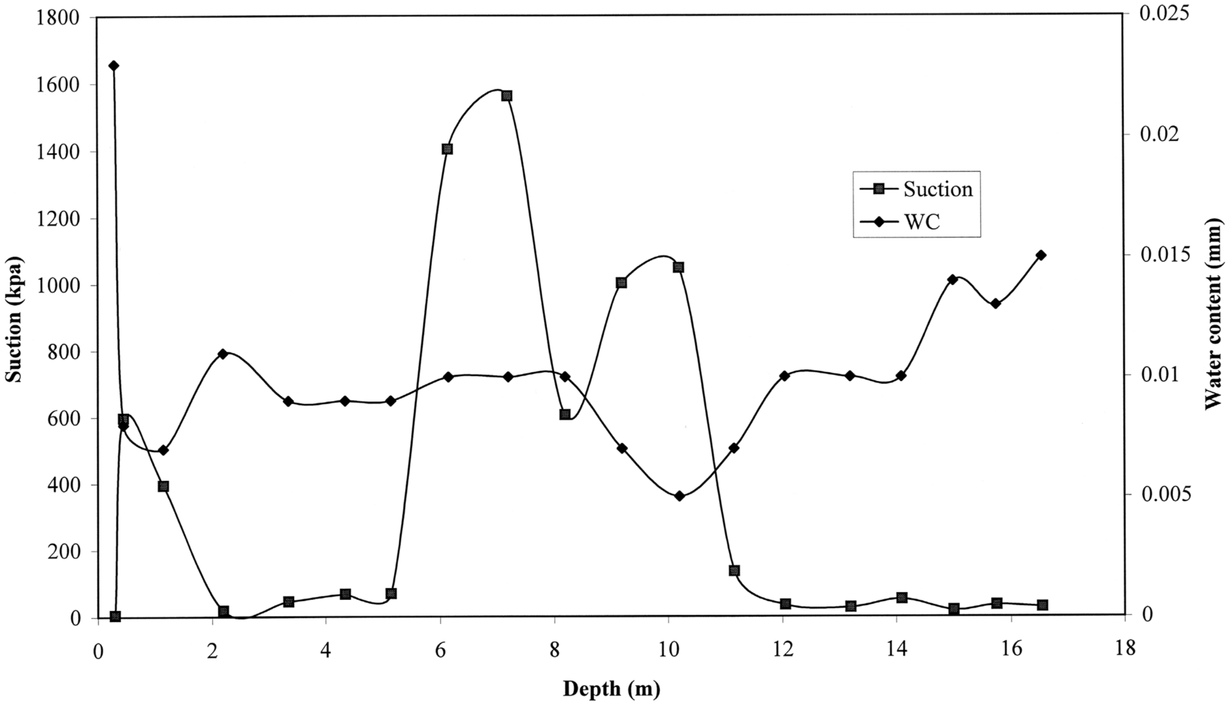

Fig. 2. Water content and suction with depth.

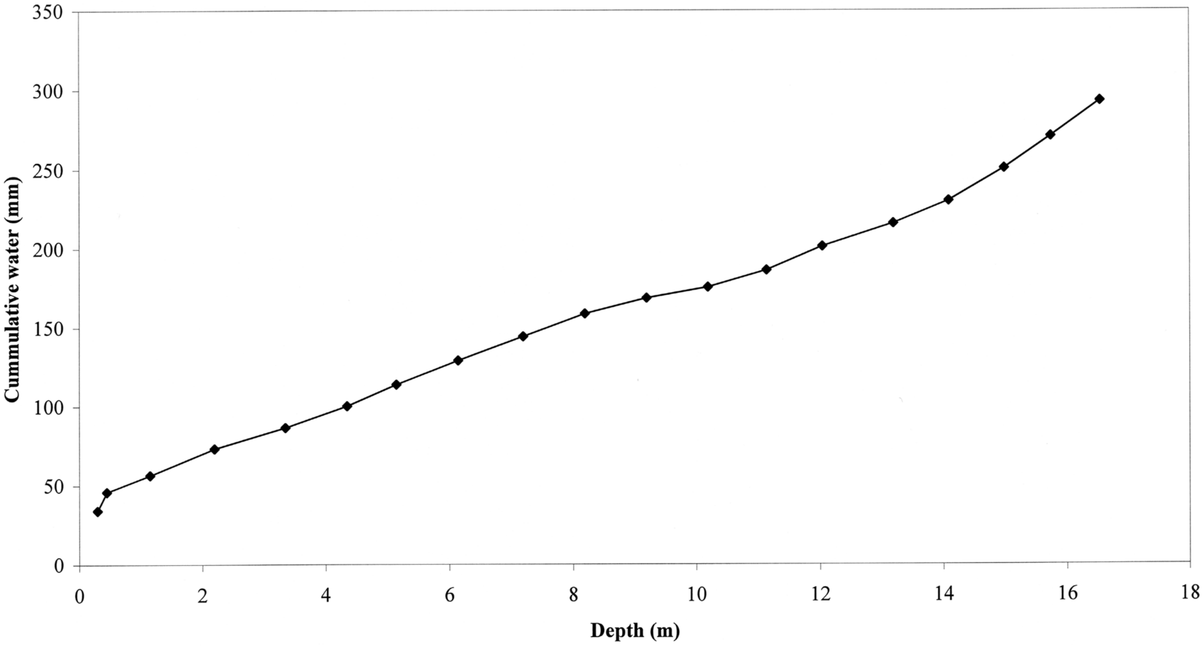

FIG. 3. Cummulative water within the profile.

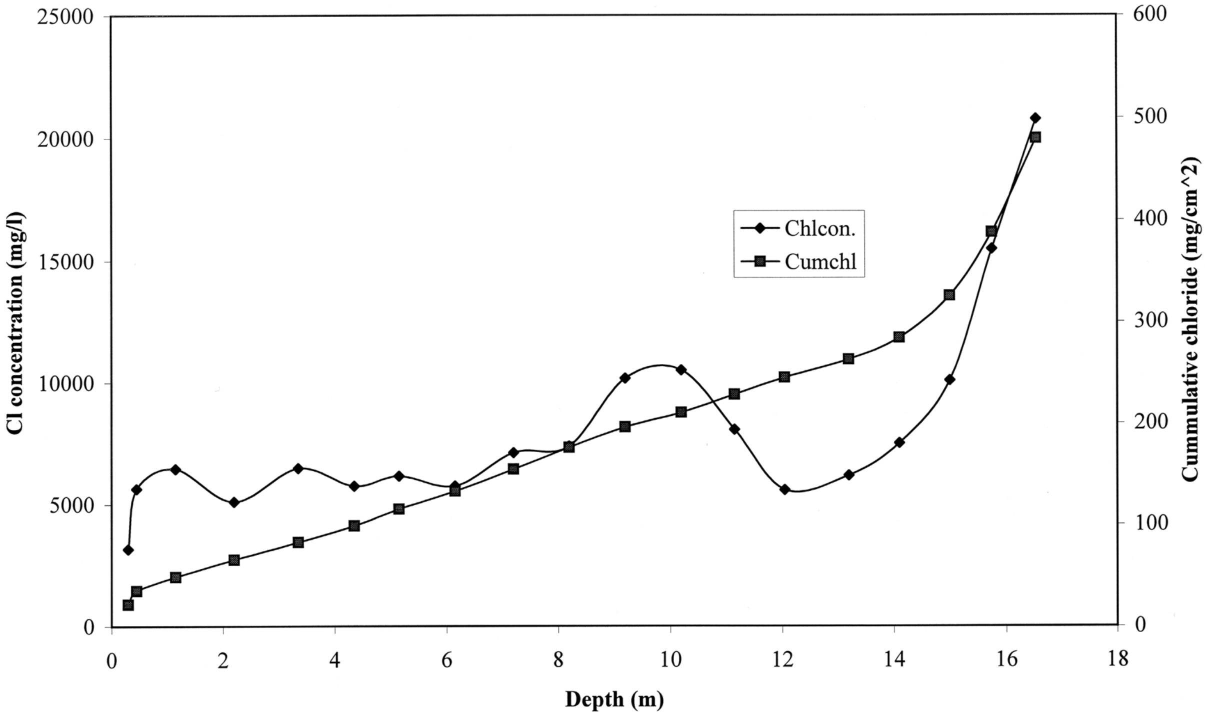

FIG. 4. Chloride concentration along the profile of the dune.

2.3. Deuterium

The deuterium data varies from 14 to -33 per mill within the profile (Fig. 5). Typical enrichment was encountered near the surface followed by depletion of isotope. Approximately the depth between 2 and 9m, a steady state condition was nearly prevailed. This indicates continuous and homogeneous shift of isotope input through the profile resulting in a relatively constant environment condition. The trend between 9 and 12m within the profile, oscillation of isotope has prevailed, indicating inconsistent condition with a trend of enrichment and depletion, which could have been resulted from the status, and nature of the recharge condition. Beyond 12m in depth, a trend of enrichment has came back indicating present day recharge.

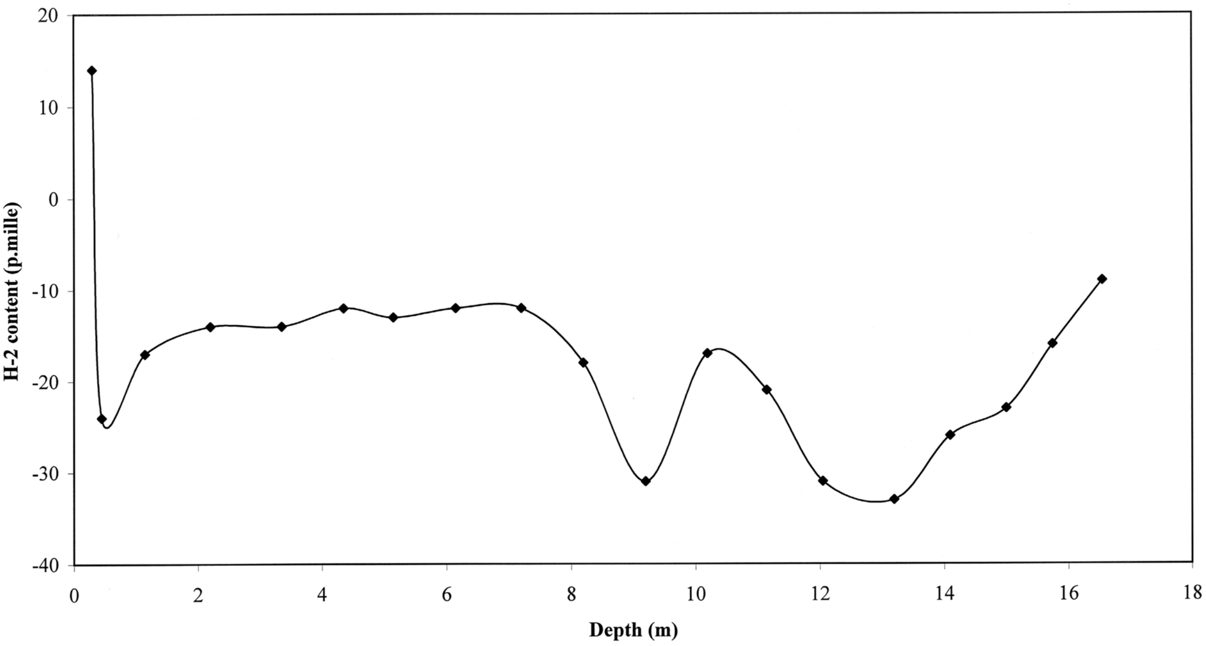

FIG. 5. Deuterium concentration with depth.

2.4. Recharge assessment

Evaluation of water volume recharged in the sand dune was conducted using the weighted precipitation in the study area (Table 1), weighted chloride concentration in rainwater and chloride concentration in groundwater (Table 2).

Table 2. Chloride concentration in rainfall data

Sources	**Date**	**Cl- Rainwater (mgl^{-1})**	**Average (mgl^{-1})**
BRGM	1982-83	12.22	
Wood &Bazuhair	1996	9.0	
KACST	1997	7.0	
KACST	1998	25	
Average for All		**13.31**	

The weighted chloride concentration in shallow groundwater in the study area was found to be 960 mgl^{-1} [3]. Chloride- mass balance method [4] was applied and presented in this way:

$\mathbf{R_w = (P * CL_p) / CL_{gw}}$ where R_w = Recharge rate

P = Weighted annual precipitation

CL_p = Chloride concentration in rainwater

Cl_{gw} =chloride concentration in groundwater

The recharge rate result obtained with the application of chloride mass balance method is about 1.84mmy^{-1} in the dune site (CRP-1). In the first progress report of the same study, the volume of water recharged in the dune site was about 1.80mmy^{-1}[1]. Both recharge rates are still very low compared to recharge rates reported in 1994 (30mmy^{-1} in the dune site and 5mmy^{-1} in the swale site.) and 1996 (13.4mmy^{-1} in the dune site) in same area using Tritium method for other projects. Applications of both methods for evaluation of recharge rate in same area at different times have shown inconsistent recharge rates although the last two events are approximately consistent. The main reasons for the lower recharge rate with the application of chloride mass-balance method could be:

- Chloride concentration in groundwater is not purely from the precipitation because it is higher than what can be expected in rainwater.
- The presence of high evaporation and precipitation of chloride salts is more likely in the study area.
- It is Likely that the dry fallout from sabkha material is the source of chloride input.
- The application of chloride mass-balance method may not be proper for this site as long as the basic assumptions for the equation are not completed.

2.5. Soil and groundwater isotope relationship

To correlate and evaluate the isotopic relationship between overlying soil and Groundwater in the various aquifers in the study area, groundwater sampling on Saq, Qassim and shallow aquifers in Qassim region was conducted. This sampling helps and makes clear the hydraulic continuity between the aquifers and rainfall. Figure 6 shows oxygen-18 against deuterium for groundwater in Qassim region. The pattern of isotope has shown spatial variation and scattering. Oxygen-18 ranges from ~0.45 per mille to about -7 per mille while

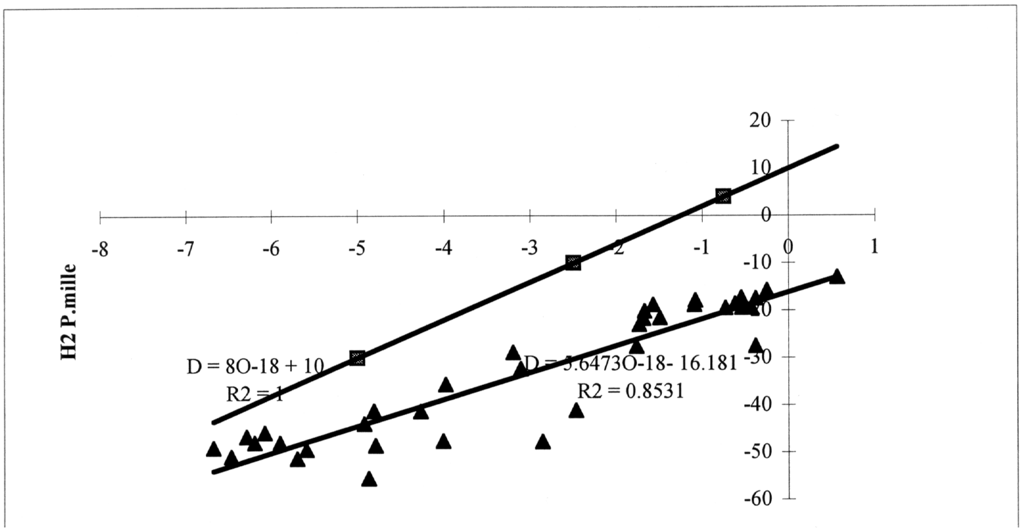

FIG. 6. Groundwater isotope in central Qasim area.

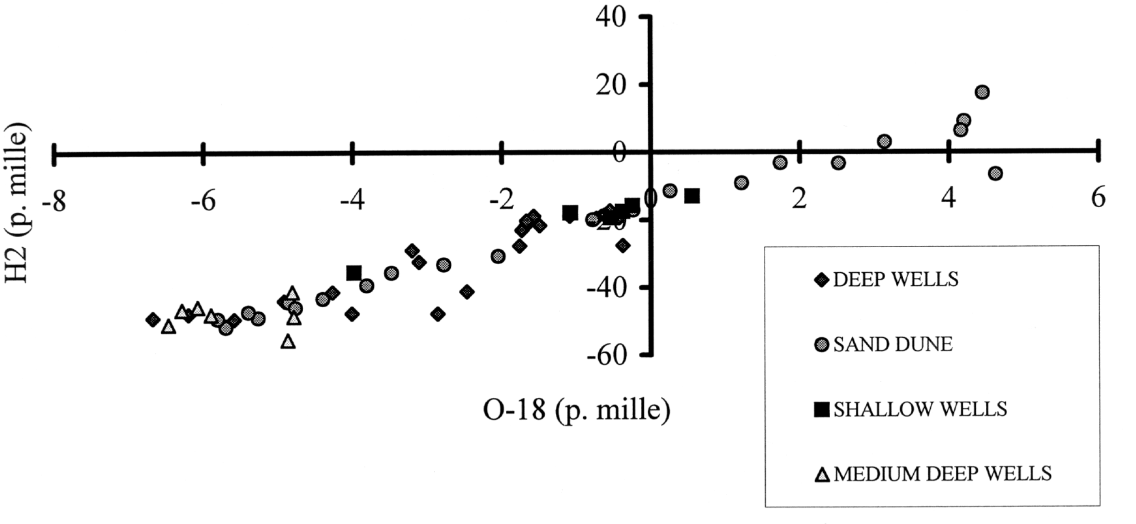

FIG. 7. Isotope comparison for deep, medium & shallow wells with sand dune waters

deuterium ranges from about -55 per mille to about -15 per mille. Comparison of isotope for deep aquifer (Saq), medium aquifers (Qassim) and shallow wells with sand dune waters are presented in figure 7. Oxygen-18 and deuterium for Saq aquifer range from -6.3 per mille to about 0.43 per mille and -55 per mille to about -15 per mille respectively. Some deep wells have oxygen-18 values lying in the range of modern precipitation (-3.5 to -2.5 per mille). For shallow wells, oxygen-18 ranges from ~ 0.56 to about -1.5 per mille and -13 to about -19.4 per mille for deuterium. This shows isotopic relationship between some deep wells tapping Saq aquifer and shallow wells tapping alluvial aquifers in the study area. There is also clear evidence of isotopic relationship between the samples of sand dune and shallow wells indicating recharge phenomena. Such phenomena are not continuous in the study area but it is confined in certain locations. This could be due to hydraulic continuity within the aquifers and between the aquifers and overlying sand dune. Oxygen-18 for medium wells (Qassim aquifer) range from -6.4 to -4.4 per mille and deuterium value range from -55 to about -40 per mille. It is likely that during the recharge there were a condensation process (cold environment) that might have caused the lighter isotope enrichment and depletion of heavy isotope [3].

In the outcrop area of Saq sand aquifer, the oxygen-18 content was -2.5 per mille, and in the deep area the oxygen-18 content was -6.5 per mille [7]. Similar values (4.62 to -5.81 per mille for oxygen-18) have also been observed in sand dune samples while shallow aquifers have similar magnitude of isotope values. Therefore, due to isotope similarities the connection between the sand dune samples and some of the aquifers like alluvial and Saq in the study area is obvious.

3. Conclusion

The area under investigation has shown variability in chloride concentration and isotopic content along the dune profile. Both radicals (chloride and isotopes) have shown monotonic patterns, indicating recharge season and dry season. Moreover, chloride mass balance method was applied in order to estimate the volume of water recharged through sand dune profile in Qasim, Saudi Arabia. The volume of water infiltrated in to the sand dunes (dune site) was very low (1.84mmy^{-1}) compared to the recharge rates (30mmy^{-1}, 13.4mmy^{-1} in the dune site and 5mmy^{-1} in the swale site) calculated in same area by applying tritium peak method in the previous years (1994 and 1996). Many factors like the source of chloride input, soil compaction, rain intensity and high evaporation in the area could cause the recharge rate variation.

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Water flow and solute transport using environmental isotopes and modeling

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Abstract. The deep unsaturated zone may be a useful hydrological archive in desert environments characterized by scant or sporadic rainfall and slow percolation of rainwater over decades or even centuries. This moisture archive provides a useful way to distinguish the net downward flow of recharge water, whereas the isotopic composition and concentration of the conservative solutes of the preserved moisture could be used to reconstruct the history of recharge under the prevailing deficient water balance. The major advantage of such coupled approach is to obtain independent estimates of groundwater recharge rates which are normally difficult to evaluate using the hydrological methods applied in the temperate zones. The study was conducted in the Shiekh-Zoweid/Raffa area in the northeastern coastal strip of Sinai Peninsula. Bore-holes were dry-drilled in a line perpendicular to the sea shoreline (using an 8-inch diameter hand-operated rotary rig) for the unsaturated sediment collection from successive 0.5m thick layers down to a depth of 20m. Samples were investigated for the moisture contents and the chemical and isotope composition of this moisture was determined. Physical parameters were also assessed including porosity and volumetric moisture content. Chloride mass-balance was used to calculate recharge rates through the unsaturated zone by predicting the position of the 1963-Tritium peak in the unsaturated column. Analysis of moisture, chloride and deuterium profiles showed three principle peaks (along with minor ones) in Karafin site indicating few major recharge events that have taken place during the last few decades. Adjustment of these episodes has also been attempted using two historical major rainfall events (known from nearby meteorological stations). Application of the methodology in water resources management in arid regions is discussed.

1. Introduction

Objective

The main purpose of the present study is the quantitative estimation of the recharge rate and assessment of recharge history from the chemical, isotope and moisture archive preserved in the relatively deep unsaturated zone of a coastal desert area, with reconstruction of calendar years of higher precipitation events in order to rebuild the “rhythm” of the dry and wet succession during the few last decades in the northeastern coast of Sinai Peninsula, Egypt.

This is approached by a preliminary test of solute acquisition mode in the saturated zone (shallow groundwater, 15-30m deep) for selecting an area suitable for recharge estimation by studying the unsaturated zone. The selected area was afterwards investigated for the chemical and isotope archive in the moisture retained in the sediments of the vertical section from land surface down to nearby the water-table using the CIMPA conventions (see: “Moisture and Chloride Archive in the Unsaturated Zone” and “Position of the 1963 Tritium Peak in the Vadose Zone” and the computer spreadsheet model CHLEAR prepared by the author for the present work).

Old environmental archives in the great Sahara

North Africa territories (and the great Sahara in general) have known strong pluvial periods (that alternated with arid epochs) during long times in the Pleistocene. Other two relatively humid pluvial periods have also existed in the climatological context of the present interglacial era of the Globe. This transposition abruptly ended-up (since few thousand years in the Holocene) by the installation of the extreme aridity that the Great Sahara knows today. The present interglacial era began to dominate the Globe since the start of the Holocene when the Earth climatic conditions again became governed only by the orbital parameters of Earth movement (i.e. when the great glacial fields - *inlandsis* - of high-latitudes in the northern hemisphere have almost disappeared and their major effect on the climate of the Great Sahara vanished).

Compared to the Pleistocene rainy times, the Holocene humid times seemingly have known modest precipitation rates with "seasonal rhythms" of rainfall rather than being "well-distributed over the year" (Rognon, 1989 and Fahmy Hussein, *in Arabic*, 1999). In fact, North Africa has known two modest pluvial periods during the Holocene: the first appeared by the start of the era, and the last apparently terminated since few (4 to 5) thousand years, Thereupon, rigorous arid conditions have been installed and lasted for about 4000 years until present.

However, even during the last extremely arid few thousand years, the southern coastal areas of the Mediterranean seemed always had somewhat attenuated aridity. These areas were relatively humid (compared to the inland areas of the Great Sahara) due to local topography or ambient factors (e.g. high topography in northern Morocco, Algeria and Tunisia, or winter "trough-initiated rains" in the low-laying littorals of both Libya and Egypt).

Since 4000 years, a famous anticyclone is permanently superimposed on the Great Sahara and hampers the arrival of important humid air-masses between the southern Mediterranean coast and the Capricorn (Rognon, 1989). This singular situation governs the regional climatic conditions and is considered responsible of locking the advent of significant rainfall to the Sahara in general. However, the ingress of winter-troughs (which is an outstanding local climatic feature) gives rise to the fall of modest to low winter precipitation at the Mediterranean coast of Egypt. This situation could have been persisting along the last few thousand years.

In fact, the highest annual precipitation rates are registered at present in the northeastern corner of the country, e.g. at the downstream of El-Arish valley in Sinai peninsula (where precipitation is almost 150-200 mm/year), and further to the east (where the annual rainfall is somewhat higher - in the range of 200-300 mm/year-), in particular at the Shiekh Zoweid (or "Zoyed") - Rafa (or Rafah) band (laying nearby Gaza Strip on the northern part of the Egyptian-Palestinian boarders). Also, air temperatures and values of air relative humidity in these sectors are clement, i.e. the desert conditions are almost due to low precipitation only.

The reconstruction of paleoclimatic conditions is an important issue in the integral study of the present-day desert environments. It is regularly invoked in order to understand the ways the local sedimentary formations have been deposited during the geological times, and also to elucidate the old environmental conditions (including precipitation).

For these ends, knowledge on the "last" changes in the geological facies is usually induced from information provided by various research methods (like the isotope dating of organic carbon, study of pollens, diatoms, foraminifera, cardiums, investigation of prehistoric (specially Neolithic) man-made tools found in lacustrine deposits, inspection of ocean and marine deposits and reconstruction of the glaciation events as archived by the 18-O negative peaks in the biogenic marine carbonates). Recently, the chemical and isotope contents of moisture preserved in the unsaturated zone profiles (Cook et al, 1992, Edmunds, 1998 and Edmunds et al, 1999) became a valuable method for the assessment of paleorecharge and paleoclimatic conditions.

The change of sedimentary facies (and sedimentation rates) are used in order to interpret the evolution of the Quaternary climates (in terms of cadence of successive arid and humid periods) in the Great Sahara. Closer the studied epoch from present, more informative would be the observations, higher would be the resolution of the time-scale assigned to events, and also more confidence could be engaged with the suggested interpretations (like the presence of paleo-lakes, old river terraces,… etc.).

Since the “rhythm” of the arid climate installation (that started to preponderate during the last 4-5 thousand years in the Great Sahara) is still “playing” under our eyes, we can interpret the most recent climatic events from the sedimentological and moisture archive using several analytical means in order to better understand our present-day environment which has continuously been subjected to old anthropogenic impacts during the second half of the Holocene. In particular, higher interest should be given to the last few centuries (or decades) since the factors that were responsible of their climatic conditions could be a part of a whole gradual climatic change that is actively acting at present.

The recent unexpectedly violent thunderstorms that stroked into the southern and middle Egypt in November 1993 and later have given place to local wadi over-flow that increased the public and official interest in the desert climate issue. Moreover, the famous recent drought that was installed (from 1968 to 1986) in the Sahel regions (which makes the unstable southern peripherals of the Great Sahara) is an outstanding example of the critical necessity to continuously improve our understanding of the meteorological and hydrological conditions governing the northern belts of the Great Sahara. However, this task is still far from culmination due to poor participation of the concerned countries in the scientific study of the Sahara.

Climate change and coastal aquifers in Egypt

For the special case of the coastal aquifers in Egypt (where marine salt-water intrusion could halt or control the development of local groundwater), climate change is a primordial question since it implies changing the precipitation rate and aquifer replenishment. Despite the fact that the reason of such interest is obvious, the strategy to tackle it (on both the scientific and natural resources management grounds) is not facile. Moreover, in order to compensate low precipitation and its temporal massing (rainfall in few days each year, mostly during winter months), a source for supplying complimentary irrigation is in fact needed, and is already obtained by increasingly pumping the coastal aquifers, in particular in Sinai.

Additional fresh water resources are also required to supply humans in the urban zones, including tourist installation activities in the distinguished coastal sites, (Marga 1989 and Fahmy Hussein, 1996, *in Arabic*). This additional exigency stands behind pumping more groundwater (in particular during the dry season) from the coastal Mediterranean strips of North Africa (with the severe impact that unplanned anthopogenic practices would imply on an already fragile natural aqueous system). Moreover, under the prevailing poor management of the natural resources, administrative decisions are usually taken on the grounds of limited data (or even without any data) due to local socio-economic complications. This makes the need for the participation of the scientific community in improving the situation more than obvious.

Moisture, chloride and isotope Vadose-Zone archive

The estimation of rainwater percolation rates and groundwater recharge under the low precipitation rates prevailing in the semi-arid to arid zones is known to be a difficult task. However, this estimation is the corner-stone of any sound regional management of water and land resources that aims at the fulfillment of the economic and social finalities that would take sustainability considerations into account. Unfortunately, the application of the conventional hydrological methods for this intent in deserts could suffer from high uncertainty. However, the environmental tracers including chloride, Tritium and Chlorine 36 (Allison et al, 1994, Cook et al, 1994 and Phillips, 1992) have proved helpful in this respect.

The upper formations of the Sinai Mediterranean coast are mostly made-up of fine Quartz sands. These systems could have been sufficiently subjected to leaching during the last few thousand years (by the low winter rainfall as discussed above) to the extent that the non-atmospheric solutes (accumulated during prior times by old marine transgression) were almost completely removed from the vadose-zone and even from the shallow aquifer in favorable coastal areas.

Rainwater infiltration through soil and deep percolation in the sediments of the unsaturated zone could be considered as a homogeneous downward movement by a piston flow toward the water-table. This moisture flow pattern in the unsaturated sediments above the water-table is accompanied by a mass-balance of conservative solutes (Scanlon et al, 1997, Gaye and Edmunds, 1995, Allison et al, 1994, Edmunds et al 1992, Edmunds, et al 1991 and Scanlon, 1990) as applied to desert soils in the USA, the coastal sandy formations in the western part of the Sahel region in Africa (in particular in Senegal) and in the Australian desert.

In fact, the downward movement of moisture through the aeration-zone is subjected to water losses by evaporation, and solute concentration would consequently gradually be increased. Accordingly, the observed contents of the conservative dissolved species (mainly chloride) of meteoric origin can be viewed as resulting from successive “input pulses and evaporative adjustments” under a steady-state flow system (for water), and a mass-balance for conservative solutes. For Cl, there would be an “input” signal (equal to the mean Cl concentration in rainwater multiplied by the annual precipitation rate), and an “output” signal (equal to the mean Cl content in the unsaturated zone multiplied by the annual recharge rate); the input and output signals are equal.

This “conceptual chemical model” for the unsaturated zone assumes that there are no sources of chloride other than: a) the meteorological input, and, b) the evaporation-dependent increase of Cl concentration in the preserved moisture during its net downward movement in the saturated zone. This assumption is likely fulfilled only in the vadose-zone below an upper “mixing” layer, whereas in the upper mixing layer itself the steady-state moisture flow principle is not applicable (Cook et al, 1992). Only when the assumption is applicable, recharge rate could be estimated (knowing mean Cl content in rainwater, mean annual precipitation rate and mean Cl content in the unsaturated zone below the upper mixing layer).

Accordingly, it is important to have an independent criterion to judge that no additional Cl input is arriving to the system from sources other than the Cl atmospheric input. Therefore, the area where such Chemical-Moisture Profile Archive (CMPA) could be used for the assessment of recharge rate should be properly pre-selected. A method based on the frequency distribution of conservative dissolved ions in groundwater (Erikson, 1975) is very useful for this particular purpose. It is applied in this work (as shown in the discussion; see the part entitled “Preselection of the Study Area Using Erickson Concept”).

CMPA could be enhanced by the introduction of the isotope archive of moisture in the unsaturated zone to be a Chemical-Isotope-Moisture Profile Archive CIMPA (see: “Analytical Measurements of Bore-hole Sediment Samples”).

Spatial variations of recharge rates

Applying CMPA for the unsaturated zone in the coastal desert areas, a value for groundwater recharge rate can be estimated. Chloride profile archive is considered as a cheap and agreeable methodology based on coherent water flow and solute mass-balance principals (Scanlon, 1990). Another recharge rate estimate could also be obtained from the isotope data (Tritium profile archive) for the same set of sediment layers collected from a single auger-hole. Due to the fact that Tritium contents are rapidly attenuating since the famous peak of 1963, the few following years are the unique chance for Tritium use in this regard in deserts (in the temperate zone areas, this chance has been lost since the 1963-Tritium peak has already arrived to the water-table due to the high recharge rates prevailing under these climates). However, it would be more reasonable to dry-drill several bore-holes in the same region in desert (and collecting samples from fine vertical intervals) to representatively cover the studied area in order to get a complete image about the spatial distribution of recharge rate changes in the catchement (Edmunds and Gaye, 1994). Eventually, this enhancement would be carried out in the framework of a regional water management appraisal in coordination with the concerned local and/or national authorities.

2. Study area

Locality

The areas where rain-fed aquifer recharge is taking place under the prevailing arid climatic conditions of Egypt are limited to the coastal plains of the Mediterranean Sea in the north of the country (in particular at Mersa Matrouh and Alexandria Governorates on the northwestern coast terminated at the Egyptian-Libyan borders, and at Northern Sinai Governorate on the northeastern coast ended-up at the Egyptian-Palestinian-Israeli borders). In the most southeastern corner of the country (at Shalateen-Halayb Triangle on the Red Sea coastal plains limited at the south by the Egypt-Sudan borders), there is also a potential of present-day recharge which is not yet studied or understood to any substantial extent. In these few limited coastal areas, rainfall is in the order of about 100-150 mm/year and rarely exceeds 250-300 mm/year. However, it is believed that precipitation could exceptionally reached 450 mm or more in few abnormal years per century in local the most northeastern corner of Sinai peninsula, (The National Meteorological Authority of Egypt, personal communication, 1999).

Sinai is a quasi-triangular peninsula that makes an area of about 61 x 10^3 Km^2 i.e. 6% or ☎ of the Egyptian territory, (Gamal Hemdan, 1992). Rainfall distribution over the peninsula is characterized by a strong decline (from 300 mm/year in its most northeastern corner, at Rafa, to 20 mm/year in its southwestern boundary on the Suez Golf). “Overall, the annual average rainfall for the entire Sinai Peninsula is 40 mm, of which 27 mm is estimated to come from individual storms of 10 mm or more” (cited from Zahran and Willis, 1992, Ch. 5, page 268). The mean annual maxima and minima of relative humidity at El-Arish is 79% and 50%, respectively, and mean annual evaporation (estimated by the Pitche method) is about 4 mm/day. Minimum winter temperature at El-Arish is 14°C, whereas maximum summer temperature is 30°C, and winds are generally gentle and do not exceed 10 knots (previous reference). Since the few investigations carried out on the study area are mostly dealing with the geomorphology of the natural drainage pattern, no substantial information is available in the literature as regard to the fractions of rainwater that would reach the water-table and effectively replenish the local aquifers.

The memory of local population (and the incomplete official registers) retains the arrival of torrential floods in Wadi El-Arish (and in other major wadies in Northern Sinai). In fact, brief but heavy thunderstorms could occur in some exceptional years and cause wadies to overflow. Extreme exceptional events have already occurred in 1947 and 1975 (records of The National Meteorological Authority and Northern Sinai Data Base, personal communication, 1999), where runoff discharge to El-Rawafaa dam exceeded the discharge of “ordinary” years by a factor ranging from 6 to 60 times, and the exceptional total flood exceeded the normal ones by a factor ranging from 10 to > 20 times (Gamal Allam, et al, 1992). These sporadic strong floods could be so singularly violent to the extent that infrastructure and proprieties would be destroyed and surface soil eroded.

Despite the low precipitation rate, rainfall would be effective in recharging the local aquifers due to the fact that precipitation events occur during few days per year (mostly during winter months) when weather conditions are favorable for low evapotranspiration losses (clement temperatures, gentle wind speed and moderate values for air relative humidity). Also, the upper formations in these coastal areas are mostly made-up of highly permeable sand deposits ("raised beached" that were formed due to successive lowering of the maritime water level, Gamal Hemdan, 1992, page 144) that could allow rapid infiltration of a fraction of rainwater, and consequent deep percolation down to the water-table.

However, the usual scenario of infiltration and percolation known for the temperate and humid regions needs that successive precipitation events should be separated only by relatively short intervals during the rainy season each year before moisture can percolate into the aeration zone (www.stockton.edu/~epsteinc/webber/aeration.htm, 1999). However, under arid to semi-arid climates, moisture pertaining to any given year in the unsaturated zone could be viewed as "pushing" the prior water pulses (residual from earlier years) that consequently slowly move downward over the years. The resultant vertical pattern of moisture profile could be considered as an archive of rainy years (appearing as high volumetric moisture peaks) separated by drought years (appearing as low volumetric moisture peaks). Moreover, and the whole moisture profile could represent a vertical sequence of wetting and drying fronts reflecting both downward (net recharge) and upward flow (evaporation).

Figure 1. Sinai Peninsula, Egypt.

Geological framework of northern Sinai coast

Five geomorphic provinces are recognized in Sinai Peninsula (Fig. 1) from north to south, namely the Mediterranean Foreshore, the Mobile Platform, the Northern Stable Platform, the Southern Stable Platform and the Southern Mountain Platform (Gamal Hemdan, 1992 and Dames and Moore, 1985). In the present research we have selected the northern coast of the peninsula for the IAEA Coordinate Research Program "Isotope-Based Investigation of the Unsaturated Zone of Semi-arid Areas" (Research Contract # 9246/RO). Along the 220 km Mediterranean coastal strip of the peninsula (distance measured as straight line on a west-east direction), considerable change of the geological setting and the groundwater hydrochemical facies are detected from west (at the Suez Canal) to east (at the Egyptian-Palestinian-Israeli borders).

At a little distance to the east from Port-Said city (on the Suez-Canal), the "Sahl El-Tina" clayey plain extends for about 43 km. To the east/northeast of these Pleistocene Nile alluvial deposits, the El-Bardaweel lagoon system is stretching as a shallow maritime water belt for about 95 km which is about 40 km wide except on the eastern arm (Zaraniek) which is only about 3 km wide. To the south of this lagoon, the coastal plains become abruptly covered by extensive unconsolidated Quaternary sand dunes and undulating terrain dominated by stable sandy deposits which are few tens of meters thick. The same type of terrain is extending for about 82 km far from the eastern borders of this marine lagoon up to the Egyptian-Palestinian-Israeli borders. This most eastern territory is gently sloping northward to the sea and very occasionally covered by eolian Quartz sand dunes and/or Quartz loam materials underlain by consolidated calcareous sands (old beaches of a type locally known as "Kurkar" which is a type of aged marine "caliche"). This coastal plain is selected for the present study. Soil site and profile description is proceeded using a worksheet (RESITE) prepared by the author. The recent wind-blown fine sands superficially interchange with finer loamy sediments (or stabilized sand dunes) on the coastal strip and extend to a distance of about 10-20 km southward inland far from the shoreline. Vertically, the upper formations (40-80 m deep) are made-up (from the top - land surface - to the bottom - arbitrarily defined at the sea mean water level -) of one or another of the following successions (M. El-Ghazawi, 1992 and references cited in Abdel-Samie, 1996):

(1) two formations:

- **a) recent sand dunes (RSD).**
- **b) sandy loam "red bed" (SLRB).**

(2) three formations:

- **a) recent sand dunes (RSD).**
- **b) Kurkar (K).**
- **c) sandy loam "red bed" (SLRB).**

(3) three formations:

- **a) loamy topsoil (loess) (LT).**
- **b) Kurkar (K).**
- **c) sandy loam "red bed" (SLRB).**

The vertical alteration of these facies is believed to indicate on the modification of deposition environments that were characterized by alternation of pluvial and arid climates during the Late Quaternary and the early Holocene. In particular, the sandy loam "red bed" (known as the Sultani deposits) are remnants of the terraces formed by old drainage patterns reflecting a famous pluvial that dominated the Sahara during the Late Pleistocene (Rognon 1989) and extending from Morocco and Tunisia in the west to Palestine in the east.

Below the upper 70-80 m thick sands, the geological formations change to about 600 m thick shell layers or dark marl shale (belonging to the Miocene), Underneath, the log contains 700 m thick Oligocene sands and clays, Eocene limestone, chalk and marl followed downward by Lower Cretaceous Nubian sandstone (that makes 300 m thick deposits) laying on 700 m thick Jurassic limestone and marl which is bottomed by 600 m thick Carboniferous sandstone and limestone formations. The shallow groundwater stored in the Quaternary upper deposits is developed in Northern Sinai, whereas deep groundwater of the Nubian aquifer is still under study for future development in order to supply the agricultural expansion in some sectors inland far from the shoreline, in particular to the southeast of El-Arish city.

Hydrology of northern Sinai coastal strip

The coastal sector between Shiekh-Zoweid and Rafa (forth sector in the following discussion) was arbitrarily preselected for the present study since it is capped by more or less stabilized sand dunes all-over the vertical section (from land surface to the water-table) or locally bottomed by "Kurkar". In this upper sandy aquifer, there is a fresh groundwater body (flowing under unconfined conditions) floating on marine groundwater. Also, in many areas there is a second groundwater body (flowing under semi-confined conditions) in the underneath "Kurkar" formation.

The isohyte lines of both aquifers (Sand and "Kurkar") are extending more or less parallel to the shoreline, and the general groundwater pattern is governed in the unconfined (Sand) and semi-confined ("Kurkar") aquifers by a dominant northward flow direction discharging freshwater to the sea. The hydraulic gradient is obviously lower than the slope of land surface in both aquifers. In the coastal strip delimited between the shoreline and an arbitrary locus line (located at 10 km far from the shoreline inland and parallel to the shoreline), land surface is dripping towards the sea by 65 to 50 m (from +75 or +50 m to +10 or 0 m amsl), whereas the water-table of the sandy aquifer drops 6.5 m (from +6.5 to 0 m amsl), and the groundwater peizometric level declines by 3.5 m only (from +3.5 to 0 m amsl) in the "Kurkar" aquifer. Consequently, land slope is around 0.500 % whereas the hydraulic gradients are in the range 0.065% to 0.035%, that is to say land surface slope is 10 to 15 times greater than the slope of the water-table, and the hydraulic gradient of the Sand aquifer is almost twice that of the "Kurkar" aquifer.

Starting from the middle of the lagoon on the west, to the Egyptian-Palestinian-Israeli borders on the east, the coastal strip extends from a "west/southwest" direction to a "northeast/east" direction and shows a definite increase of annual rainfall (from a minimum of about 100 mm to a maximum of almost 300 mm per year). The coastal strip was arbitrarily sub-divided, for the purposes of this study, into four geographic sectors (distances as reported on the coastal highway which is 235 km in length):

(1) from Suez Canal to Bir El-Abd (80 km long).
(2) from Bir El-Abd to El-Arsih (95 km long).
(3) from El-Arish to Shiekh Zoweid (35 km long).
(4) from Shiekh Zoweid to Rafa (25 km long).

The first sector was not considered in this research since it will be irrigated using Nile water (arbitrarily 1:1 mixed with agricultural drainage waste water flowing out from the eastern region of the Nile delta) through a canal that passes eastward beneath the Suez Canal to the northwestern and middle-northern Sinai. The local population in the second, third and fourth sectors makes use of shallow pumping wells as well as surface galleries (excavated in the topmost sand deposits to directly expose groundwater in tiny pools) to supplement local precipitation for irrigating lands growing fruits and vegetables. Since the cultivated areas were extensively increased during the last few decades (Moustafa El-Ghazawi, 1992), the number of pumped wells increase and over-pumping becomes alarming.

Groundwater samples of Sheik Zoweid-Rafa sector

Groundwater samples were collected from operational shallow wells and excavated galleries (locally known as “Tamilah”) in the above-mentioned fourth sector of in order to check if the groundwater system is predominated by solute acquisition through wet deposition and evaporation. The Cl frequency distribution and Erikson concept were used to interpret the data. Chemical data provided from an earlier study (Abdel-Samie, 1996) was integrated in the frequency distribution study since it covered the second, third and fourth sectors of the Northern Sinai foreshore coastal plain. The sector that proves to be almost free of mixing and dissolution might be considered as suitable for estimating recharge using the unsaturated zone archive and chloride mass balance and environmental isotopes (the CIMPA approach adopted in the present study), whereas the area dominated by water mixing and solute dissolution should be excluded from the board of the present study.

Oxygen-18 and deuterium were also measured in the groundwater samples collected from the shallow wells and galleries in the fourth sector. The isotope data is plotted against the TDS (Fig. 6) to demonstrate the qualitative isotope-chemical affinity. With this qualitative relationship we can distinguish - once more - the mode of solute acquisition (rainfall and evaporation *versus* mixing and dissolution) in order to independently verify the detachment of the foreshore coastal plain according to the dominant solute acquisition mode (see: “Preselection of the Study Area Using Erikson Concept”, in the discussion and interprettion). For the convenience of having a greater number of samples isotopically analyzed, our set of samples was enhanced by isotope data reported in the above-mentioned earlier study (Abdel-Samie, 1996). The combined data makes altogether 217 samples. Our own isotope and chemical data set makes about one tenth of the total number of groundwater samples. The earlier study had not given any attention to studying Cl distribution in groundwater by Erikson’s method for the purpose we outlined in the present study. The earlier data also was neither interpreted in terms of suitability of the different groundwater sectors of Northern Sinai coastal area for obtaining a quantitative estimate of recharge, nor it presented any appraisal of groundwater salinity origin according to the mode of solute acquisition. So, despite the fact that we make use of data previously reported in an earlier study (in order to enhance the number of observation points to check before conducting our unsaturated zone study), our present study obviously stands unique and authentic. Moreover, our study accounts for both the saturated and the unsaturated zones whereas any earlier study on the same area was only dealing with the saturated zone.

The combined data set have clearly indicated - in 1998 - that only the groundwater samples collected from the Shiekh-Zoweid-Rafa sector (the fourth sector) have a log-normal Cl distribution and also a clear evaporative trend (shown on the ^{18}O-TDS plot, Fig. 6) indicating a solute history corresponding to wet deposition, and stable isotope enrichment effected by evaporation. We will see (in the item dealing with the “closed system conditions”) that groundwater chemistry also shows that evaporation has exclusively taken place in the unsaturated zone during recharge not in the aquifer after recharge. This implies that the fourth sector (Shiekh Zoweid / Rafa) is the unique site which could be compatible with the criteria required for the application of CIMPA in the unsaturated zone. Meanwhile, the samples collected from the second and third sectors have shown a dissolution and/or mixing origin of solutes in groundwater (as indicated by the normal frequency distribution of chloride) and showed (on the Cl-^{18}O plot) an almost horizontal orientation of data points parallel to the chloride x-axis indicating solute dissolution. This implies that the attempt to use the unsaturated zone data from Shiekh-Zoyed and Rafa sector is expectedly successful for the purposes of this study.

Analytical measurements of sediment samples

The second phase of the present research was achieved by dry-boring two unsaturated boreholes (each 20 m deep) using 8-inch diameter manual rig, and collecting 40 samples (at 0.5 m intervals) per borehole in 1998. One borehole was about 1 km far from the shoreline, whereas the second was at about 10 km more far inland and both are oriented on a straight course perpendicular to the shoreline. This was followed by another two boeholes, one of them was at about 5 km from the shoreline whereas the second was at 15 km from the shoreline. Isotope and chemical analysis was carried out on all the unsaturated zone sediments (including moisture content, chloride and deuterium in residual moisture, whereas tritium is currently being measured). During the unsaturated zone sampling program, measurements of bulk density, pore-size distribution, sediment moisture characteristic curve (of samples from the upper one meter of the topsoil) and estimation of the unsaturated hydraulic conductivity (as a function of moisture content) based on measured saturated hydraulic conductivity was also undertaken. Tritium profiles and a thin section study of porosity (using plain and crossed polarized light) will also be proceeded in order to complete the image of the studied profile, and will be reported (as well as the data of the third and fourth unsaturated boreholes) elsewhere.

Chloride content of the interstitial water in the unsaturated zone is measured after moisture extraction either by direct centrifugation (Edmunds and Bath, 1976), immiscible displacement followed by centrifugation (Kinniburgh and Miles, 1983) or elutriation (50 grams moist sample plus 30 ml aliquot of distilled water) and centrifugation followed by filtration through a 0.45 μm filter paper. Moisture in the unsaturated zone can be studied using the environmental isotopes in the water molecule, namely, oxygen-18 (^{18}O), deuterium (^{2}H) and Tritium (^{3}H). Non-fractionation extraction (Walker et al, 1994) of the moisture preserved in the sediments of the unsaturated zone is systematically proceeded before measuring the ^{18}O and ^{2}H contents. The usual extraction method is based on evaporation and condensation in a closed system previously subjected to vacuum. Starting from the extracted water and using vacuum techniques, an appropriate gaseous phase is prepared for isotopic measurements. CO_2 gas in isotopic equilibrium with water is usually used in the case of ^{18}O (Roether, 1970), whereas H_2 gas is generated by reduction of water on hot Uranium or Zinc (Moser et al 1971 and IAEA, 1986) in the case of ^{2}H. In the gaseous phase, the isotope ratios $^{18}O/^{18}O$ (Epstein and Mayada, 1953 and Darling and Talbot, 1989) and $^{2}H^{/1}H$ (Drost et al, 1974) are measured on a mass-spectrometer. However, a direct method (Coleman et al, 1982 and Darling et al, 1989) for the generation of hydrogen gas (by water reduction) needed for the measurement of $^{2}H/^{1}H$ ratio has recently became a routine method that can be more rapid and particularly adequate for the low moisture content in unsaturated sediments of the arid zone. For natural water samples, after electrolytic enrichment (Ostlund et al, 1963), Tritium content is measured after enrichment (Taylor, 1975, and IAEA, 1976) using a scintillation counting method (Cameron et al 1966, Cameron, 1967 and Tanweer et al, 1982) for the detection of the low radioactivity beta particles emitted if the water sample was not Tritium-dead. However, for the low moisture content of the unsaturated sediments this would require a large amount of the moist sediment. Instead, after extraction of sediment moisture, the extracted water is converted into a gas containing hydrogen in order to measure its radioactivity using a gas counter.

Rainwater composition

As the input information (mean Cl content in rainwater) is needed, it is appropriate to have a historical record not only of precipitation rates but also of rainwater chemistry in the studied area and/or in a nearby meteorological station. The studied area is lacking a long historical rain chemistry data, however, we have Cl concentrations and isotope composition in precipitation of the last few years. Also, Alexandria station reports were referred to (Fig. 5 a, b and c) in order to review a twenty years isotope composition data set known for rainwater of northern Egypt (IAEA- GNIP, 1998). The mean Cl content for the last three years in Shiekh-Zoweid-Rafa is 16 $mg.l^{-1}$. In a study on rainwater in Israel (Herut et al, 1995) the reported data show that 58.8% of samples contain <50 $mg.l^{-1}$ Cl, whereas 29.4% has 50-100 mg and 17.6% has >100 mg (in more detail, samples with <25 $mg.l^{-1}$ Cl = 17.6%, 25-50 mg = 41.2%, 50-75 mg = 23.5%, 75-100 mg = 5.9%, 100-200 = 5.9% and >200 mg = 5.9%). From the reported data and site map for the Israeli study, it could be said that at a moderate distance in Israel far from the Egyptian-Israeli borders (25-75 km) in a strip parallel to the borders but perpendicular to the shoreline, Cl concentration in rainwater increases in an inland direction from 25 to 60 $mg.l^{-1}$ along a distance of 150 km (i.e. there a slight inland gradient of 2.3 mg/10 km).

3. Discussion and interpretation

Preselection of the study area using Erikson concept

In order to use the isotope and chemical archive preserved in the unsaturated zone (using the steady-state chloride profile approach and the 1963-Tritium peak) for estimating the recharge rate under the arid to semi-arid climate conditions prevailing in the Mediterranean coastal zone of Sinai peninsula, it is essential to be quite sure that groundwater of the selected area is characterized by a dominant solute acquisition mode dictated only by two processes:

(1) ***wet deposition*** (ionic species in local precipitation) as origin of salinity in the unsaturated zone (i.e. there is no neither a marine origin of salinity nor transport of solutes to the selected domain from adjacent geological formations by lateral groundwater movement).

(2) ***evaporation*** is the unique mechanism that increases the initial solute concentrations of local rainfall during unsaturated flow in the vadose-zone.

In other words, the selected profiles should be free of mixing of different water bodies with dissimilar chemical history and distinct TDS contents, and should also be free of solute acquirement by weathering and/or leaching of marine or continental evaporites. This is an important condition to respect if we would like to use not only the environmental isotope signatures (^{18}O, ^{2}H and Tritium) preserved in the moisture archive of the unsaturated zone but also when we would like to use the vertical chloride distribution in particular for tracing the net water displacement toward the local aquifer and for applying the Cl steady-state mass balance in the unsaturated profile to estimate the recharge rate.

An interesting method for such verification has early been formulated by the Swedish scientist Erikson (Erikson, 1975) for appraising the origin of chloride content in groundwater when a good number of observation points is available on the regional scale. Despite the coherent theoretical basis (equation derivation) and relatively simple applicability of this method, it has unfortunately never been popularized in the hydrological studies for which it has been basically formulated.

The intent of this method is to let the user distinguish between two groups of groundwater:

(a) groundwater bodies which have gained their conservative solute content (Cl) mainly due to ***dissolution and mixing*** (in this case, a *normal* frequency distribution of chloride concentrations in regional groundwater samples should be observed), and

(b) groundwater bodies which predominantly gained their chloride contents mainly due to meteorological (atmospheric) ***wet deposition*** which was subsequently affected by ***evaporation*** during slow moisture downward percolation into the unsaturated zone (in this case, a *log-normal* frequency distribution of Cl contents should be observed in regional groundwater).

Moreover, if the studied reservoir belonged to the second group, ***an estimate of recharge rate could be obtained using the harmonic mean of Cl content*** in the groundwater samples, the ***mean Cl concentration in local rainfall*** and the ***mean annual rainfall*** of the studied area. In fact, the harmonic mean (i.e. the reciprocal of the arithmetic mean of reciprocals) could easily be obtained from a set of Cl data (note that the harmonic mean is always less than the geometric mean, which is always less than the arithmetic mean).

Groundwater chemistry

The chemical composition of the groundwater samples collected from pumped shallow wells (15-30 m deep) as well as from groundwater pools exposed in dug gullies in Shiekh Zoweid-Rafa (the fourth sector in the above-mentioned site list) is shown on Piper triangular cation and anion spaces (Fig 2) according to the famous method (Piper, 1944). Manual plotting of Piper diagrams is tedious and many computer applications have introduced codes to mechanize that task. The author of the present work has prepared an Excel spreadsheet file (called *ESCAPE*) for this duty and also for plotting other hydrochemical diagrams) which could be more agreeable to use than many store software packages. On Piper plots, samples are arranged according to the gradual increase of TDS starting from sample # 1 (Table 1). In all samples, Ca, Mg and Na + K stand for <50%, <30% and >30% of cations, respectively. For anions, Cl represents >30%, SO_4 contribution is hardly greater than 40%, whereas HCO_3 sharing is >50%. It is also clear that the groundwater chemical composition, in general, shifts from a (Ca-Na-HCO_3) to a (Na-Cl-SO_4) type accompanying the increase of salinity from low TDS values in the dilute groundwater samples (close to the initial composition of rainwater) to higher TDS values through the combined effect of processes that take place in both the unsaturated and saturated zones. With first stages of TDS increase in the most dilute wells, we observe a gradual increase in the contribution of Ca and Cl which could reflect natural changes in rainwater chemistry. In all the studied samples, a significant decrease of HCO_3 contribution with TDS increase is observed and could be considered as an indication on slid-phase precipitation (Calcite coatings on sand grains) by evaporation during recharge in the unsaturated zone. For the moderate to the relatively highly charged wells, there is also a general increase in the contribution of SO_4 accompanied by a decrease of the contribution of Ca. This second chemical shift could be the resultant of Gypsum dissolution in the saturated zone accompanied by slight Calcite precipitation in the aquifer. Since Piper plots does not provide a deep insight into the reasons of water composition change, D'Amore ionic ratios (Fig. 3) were used to elucidate the origin of dissolved species. Also, Schoeller and Stiff diagrams were plotted to follow the change of the chemical facies with salinity build-up. A worksheet (ESCAPE) is prepared by the author to graphically plot water chemical composition using 6 methods.

Origin of solutes in groundwater (D'Amore ionic ratios)

Six ionic ratios (where ion concentrations are expressed in meq/l) were calculated according to the following formulae (D'Amore, 1982):

$$A = \left(\frac{Alk - SO4}{Anions} \right) * 100 \qquad B = \left(\frac{SO4}{Anions} - \frac{Na}{Cations} \right) * 100$$

$$C = \left(\frac{Na}{Cations} - \frac{Cl}{Anions} \right) * 100 \qquad D = \left(\frac{Na - Mg}{Cations} \right) * 100$$

$$E = \left(\frac{Ca + Mg}{Cations} - \frac{Alk}{Anions} \right) * 100 \qquad F = \left(\frac{Ca - Na - K}{Cations} \right) * 100$$

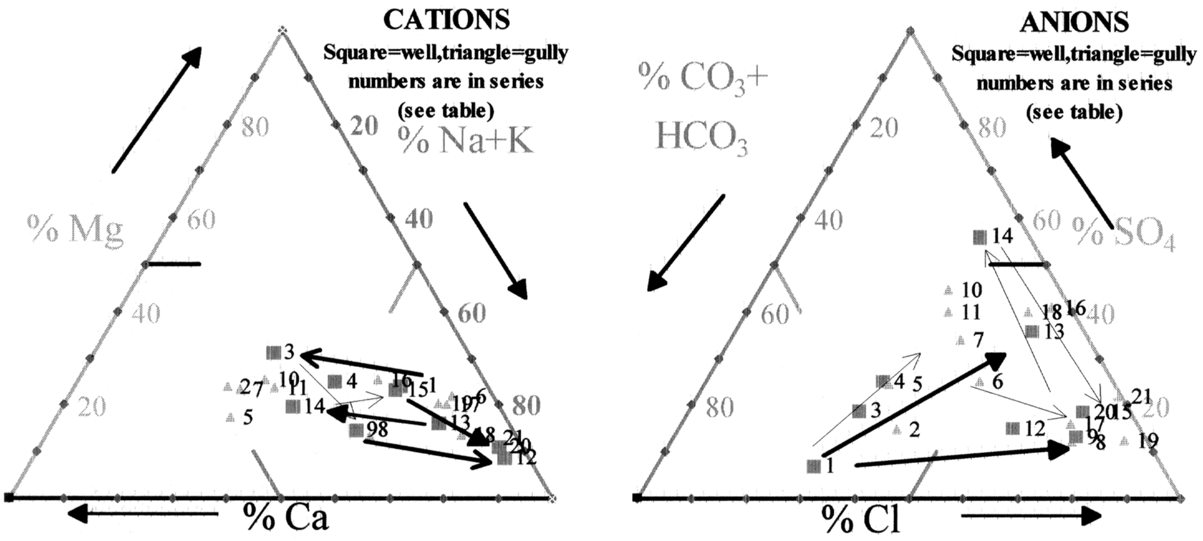
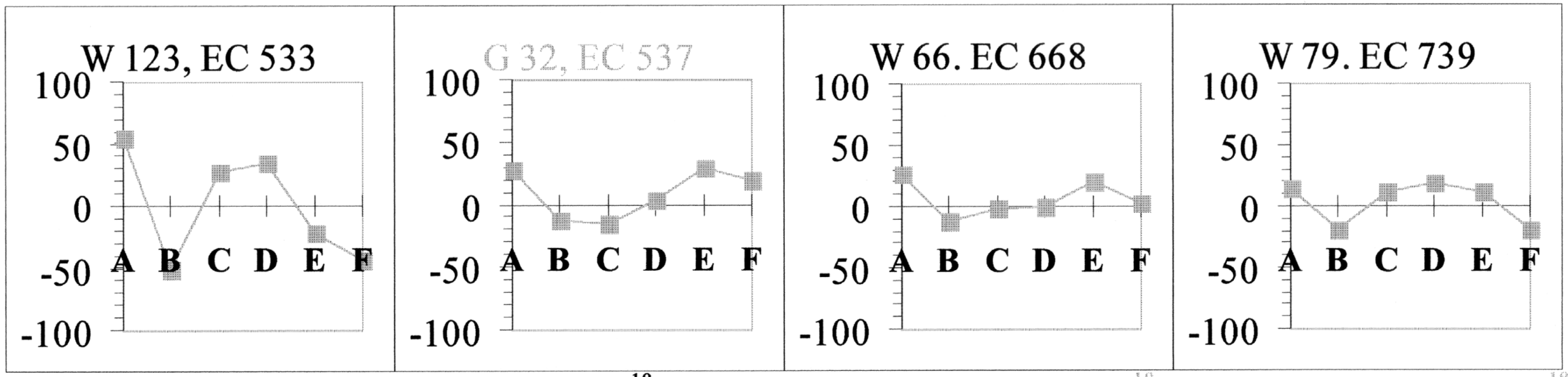


Figure 2. Piper Diagram of Some Groundwater and Gullies, Shiekh Zoweid/Rafa Sector, Northeastern Sinai (see Table 1).

D'Amore ionic ratios are given in Fig. 3 (a, b and c), where samples are arranged according to the increase of TDS. D'Amore signals (expressing the above-given ionic ratios A, B, C, D, E and F) present an elegant way to understand the major mechanisms affecting the chemical evolution of groundwater systems (see comments below each D'Amore plot), in particular those concerning the source of solute acquisition. The comments below D'Amore plots also show the major ^{18}O observations of some samples. In fact, the stable isotope content of rainwater increases with evaporation in the unsaturated zone and becomes conservative in the saturated zone if no evaporation (or mixing) takes place from the water-table. In the section "δ^{18}O-TDS Plot", we will deal with relationship of the isotope composition and the TDS and will see that these plots show that in the selected area (Shiekh Zoweid-Rafa) dissolution and mixing are by no means the dominant factors behind solute acquisition in groundwater, whereas wet deposition and evaporation are, on the contrary, the most effective mechanisms of solute evolution in the studied area. These two processes (wet deposition and evaporation) take place *a priori* in the unsaturated zone. Beside the above given discussion on Cl frequency distribution (that showed the suitability of selected area for the intent of the present study), the observations on the δ^{18}O-TDS plot (Fig 6) once more warrant the selection of this locality and proves that it is ideal for the purpose of groundwater recharge estimation using CIMPA.

Thermodynamic processing

Thermodynamic data was processed using WATEQ4F (Truesdell et al, 1974 and Plummer et al, 1976) of NETPATH software (Plummer et al, 1996). Ionic strengths as low as 0.008 are found in the dilute wells in the Shekh Zoweid-Rafa area and it never exceeds 0.080 in the relatively brackish wells and gallery samples (only one sabkha sample has an exceptional ionic strength of 2 due to intensive evaporation of surface water). Almost all samples, (except # G22 which is collected from a gully) have a CO_2 partial pressure significantly higher (Fig. 4 f) than the atmospheric pCO_2 (by a factor of 10 to 15) which could reflect the presence of moderate biogenic effect in these aqueous solutions. Due to the scarce vegetative cover, no significant soil CO_2 gas can be generated from the root zone, and the high CO_2 gas content in groundwater should either reflect older environmental conditions or slow rate oxidation of old organic matter in the aquifer but there is no way to distinguish one mode

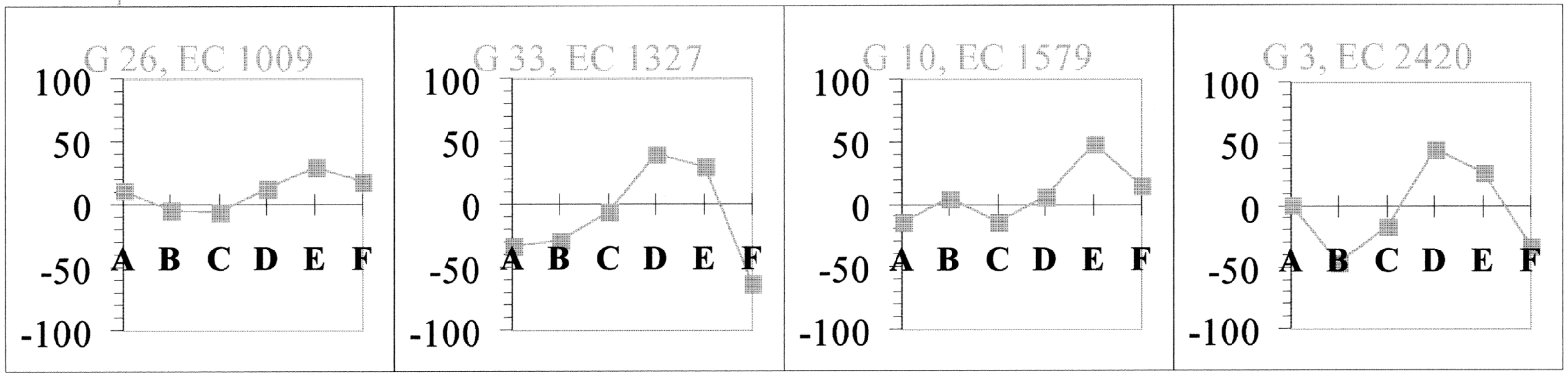


Calcite (A+&C+)
Marl (B-). Evaporites (D+)
Most depleted ^{18}O.

Rain chem. High ^{18}O, evaporation.

Rain chem. Most depleted ^{18}O.

Rain chem. Most depleted ^{18}O.



Rain chem. Depleted ^{18}O.

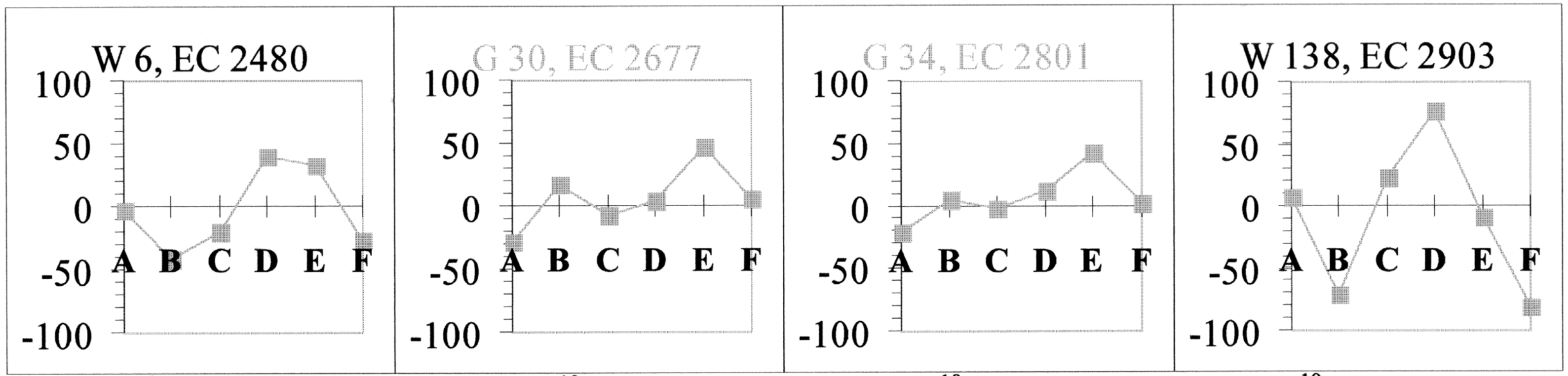
Sulfates (A-, E+)
Marl (B-). High^{18}O but moderately evaporated.

Sulfates (E+).
Evaporated ^{18}O.

Marl (B-).
Sulfates (E+).
Evaporated ^{18}O.

Fig. 3(a). D'Amore sign showing six ionic ratios

EC is reported in micromhos.cm^{-1}
W = Well (shallow wells)
G = Gully (gallery, trench or ditch of conical hollow form = "Tamilah" *in Arabic*).

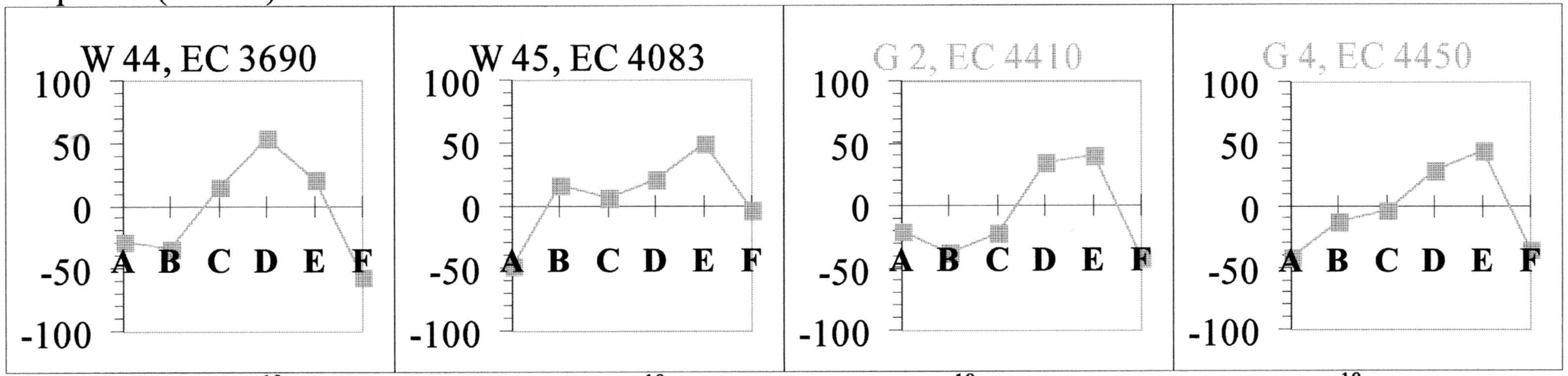


Mixing ? ^{18}O. Marl (B-). Sulfates (E+). Evaporites (D+&F-).

Evaporated ^{18}O. Sulfates (E+).

Evaporated ^{18}O. Rain chem. Sulfates (E+)

Mixing ? ^{18}O. Marl (B-). Evaporites (D+ & F-).



Dissol. ? (horizon. ^{18}O). Sulfates (A-&E+).Marl (B-). Evaporites (D+ & F-).

Mixing ? (oblique ^{18}O-TDS). Sulfates (A-&B+&E+).

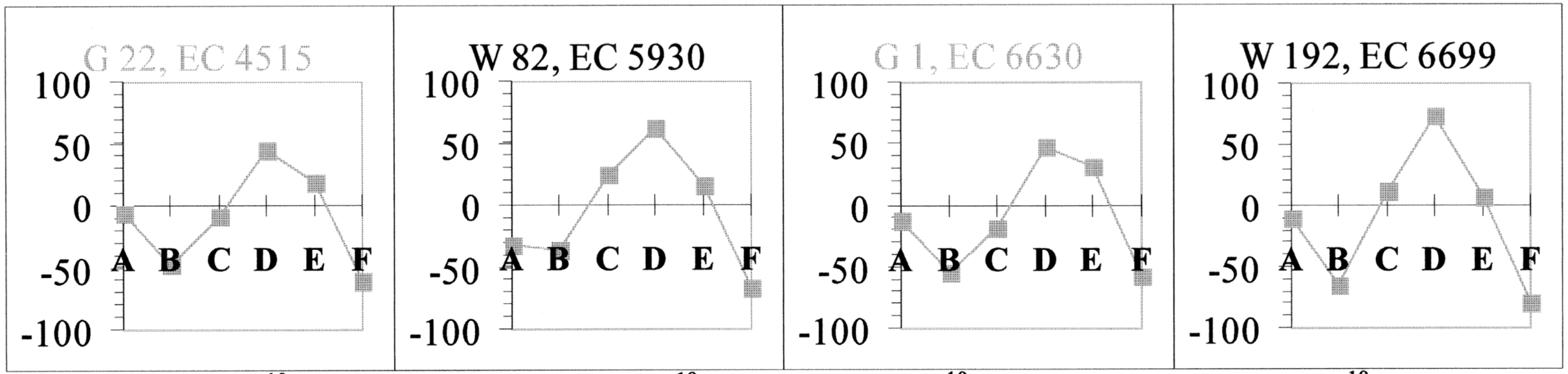
Evaporated ^{18}O. Sulfates (E+).

Evaporated ^{18}O.

Fig. 3(b) D'Amore sign showing six ionic ratios

EC is reported in micromhos.cm^{-1}

W	=	Well	(shallow wells)
G	=	Gully	(gallery, trench or ditch of conical hollow form = “Tamilah” *in Arabic*).

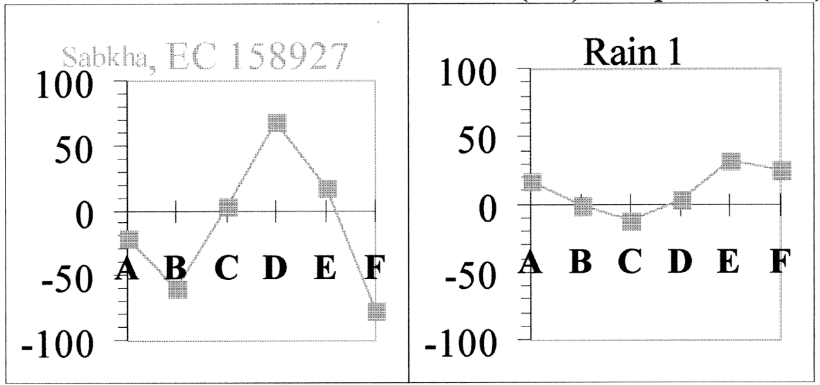


Highly Evaporated ^{18}O.

Dissol. ? (horizontal ^{18}O).
Sulfate (A-). Marl (B-).
Calcite (C+). Evaporites (D+).

Evaporated ^{18}O.

Evaporated ^{18}O.



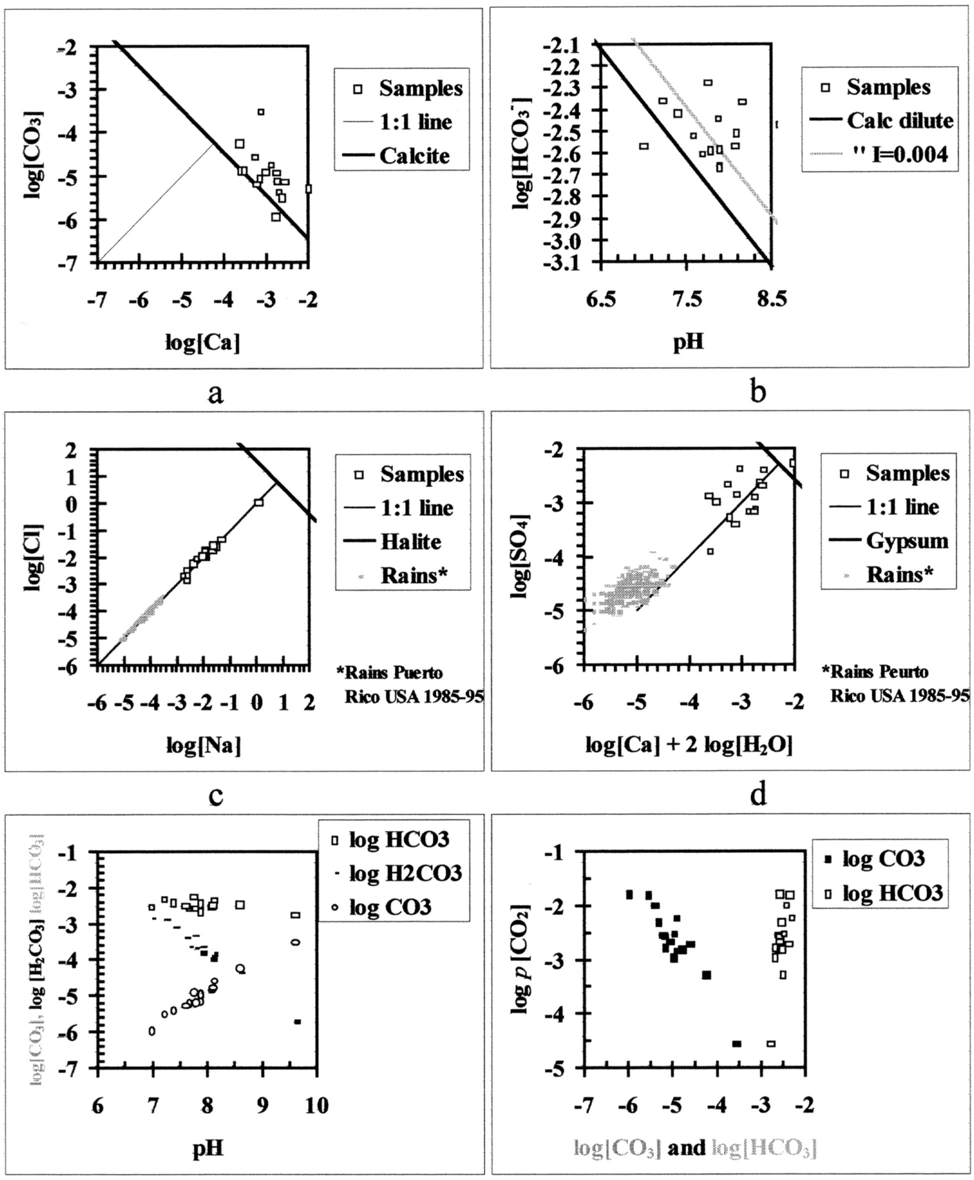
Highly evaporated ^{18}O.

Cairo rain.

Fig. 3(c). D'Amore sign showing six ionic ratios.

EC is reported in micromhos.cm^{-1}

W	=	Well	(shallow wells)
G	=	Gully	(gallery, trench or ditch of conical hollow form = "Tamilah" *in Arabic*).



a b c d e f

Fig. 4. Logarithms of ionic activities with respect tp Ca;cie, Halite and Gypsum and components of the TDIC as calculated by WATEQ4F of NETPATH for groundwater and gullies, Shiekh Zoweid/ Rafa, Northeastern Sinai.

from another without a particular study to purge out the dissolved gases and measuring its isotope composition and comparing it to the isotope composition of organic matter in the aquifer material. Also, a microbiologic investigation of the unsaturated zone material could also be helpful to elucidating the biogenic generation of CO_2 gas. However, a proper geochemical modeling using hydrochemical and isotope data (including $\delta^{13}C$ data for groundwater along the flow pathway) could give a preliminary insight into the system to account for CO_2 generation.

On the plots of log [CO_3] *versus* log [Ca] and log [CO_3] *versus* pH (Fig 4, a and b), WATEQ4F calculations show that most of the collected water samples (except one, # G3, from a gallery) are saturated or supersaturated in Calcite (Fig. 4 a). All the collected samples are largely far from saturation in Gypsum and for sure highly under saturated in Halite (Fig. 4 b and c). Saturation in Calcite could reflect the presence of carbonate solid-phases in the aquifer and/or in the unsaturated zone, and also explains the observed slightly alkaline pH values (from7.5 to 8.0) which are significantly higher (by more than 2 pH units) than the theoretical pH of any non-polluted rainwater. The saturation indices of both Calcite and Gypsum increase in a scattered pattern with the increase of ionic strength (not shown), whereas the saturation index of Halite linearly increases with the ionic strength. This could be related to differences is the mode of acquisition of calcium, bicarbonate and sulfate on one hand, and acquisition of sodium and chloride on the other hand in rainwater. The linear relationship between Halite saturation index and the ionic strength reflects a sea spry origin of Cl and Na while the scattered relationship between Gypsum and Calcite saturation indices and the ionic strength could reflect the participation of a non-sea spray origin (from reaction of rainwater with Saharan dry deposition along the pathway of the humid air-masses that give rise to rainfall in Northern Sinai) along with the sea spry origin for Ca, SO_4 and HCO_3 dissolved in rainwater. Studying Israel rainwater chemistry (Herut et al, 1995), it has been shown that four ions (Cl, Na, K and Mg) have a marine spray origin, whereas mostly Ca and SO_4 masses are 50% of sea-spray origin and the rest is derived from non-sea-spray origin (from reaction of rainwater with atmospheric dust) whereas in many cases HCO_3 in rainwater is under the detection limit as expected. An additional increase in solute content starting from the rainwater composition should be attributed to the effect of water losses during evaporation but dissolution of evaporites could also be responsible.

Closed system conditions in the aquifer

A graphic of the type log $[HCO_3^-]$ on the y-axis *versus* pH on the x-axis (Fig. 4 e) is normally used to distinguish water development under closed condition *versus* development which takes place under an open system conditions (Stumm and Morgan, 1981 and 1996). Under open system conditions water chemistry develops along straight lines perpendicular to the Calcite saturation locus line, whereas under the closed system conditions water develops along curvilinear trends that progress downward towards the Calcite saturation locus line. The particular positions of any given straight (or curvilinear) line for the evolution of relationship of $\log[HCO_3^-]$ *versus* pH are controlled by the values of the partial pressure of CO_2 gas (high pCO_2 makes the trend shifts to a higher $\log[HCO_3^-]$ on the y-axis). In the case of our set of data this plot, however, is difficult to be used for distinguishing between the open and the closed system due to lack of very dilute samples close enough to local rainwater composition.

Therefore, we used another method for the discrimination of the *open versus* the closed system conditions. We plotted the three major dissolved carbonate species (namely, $\log[CO_3^{2-}]$, $\log[H_2CO_3]$ and $\log[HCO_3^-]$) on the y-axis *versus* pH on the x-axis (Fig. 4 e). The obtained pattern shows that with pH increase, $\log[HCO_3^-]$ values are more or less constant, $\log[H_2CO_3]$ values decrease and $\log[CO_3^{2-}]$ values increase. This is the typical pattern of a *closed system* evolution (with respect to CO_2 gas) of water carbonate chemistry in the saturated zone (after recharge with rainwater having an initial pCO_2 that could be acquired not only through equilibrium with atmospheric CO_2, but probably also through dissolution of

biogenic CO_2 gas in the unsaturated zone). If the chemical evolution of groundwater was, on the contrary, developing under open system conditions with respect to CO_2 gas, we would have observed constant $\log[H_2CO_3]$, increasing $\log[HCO_3^-]$ and increasing $\log[CO_3^{2-}]$ with pH increase.

This interpretation has an interesting impact on our understanding of the hydrological and the hydrogeochemical system in the studied area. Under the relatively favorable recharge conditions that presumably lasted for few several thousand years in the Holocene, and in the absence of an upper confining strata, the groundwater system is indeed “opened” to recharge and evaporation. However, with respect to gaseous exchange with surroundings, the system proved acting as a “closed”. This means that recharge water acquires its dissolved CO_2 content from the atmosphere, (and from biogenic sources that can be verified using $\delta^{13}C$ data when it is made available) before arrival to the water-table. After arrival to the water-table, any further groundwater further development will take place with no gaseous mass-transfer from or to the aquifer (the system is closed to gases). The hydrological importance of this closed system is that if the groundwater is closed to gaseous exchange with the surroundings, consequently there is a chance that no evaporation takes place from the water-table (i.e. there is no evaporation after recharge), or at least if such evaporation occurs it is really minimized and can be negligible and all observed evaporation is only taking place in the unsaturated zone during recharge. When this aquifer is studied using ^{13}C and ^{14}C data and a geochemical mass-transfer model (or a hydrodynamic flow model that includes solute transport within the aquifer) is applied, the closed-system situation must be respected in order to get representative model output.

δ^{18}O-TDS plot

Our limited isotope data for groundwater in the studied area can be investigated with respect to three processes that can be distinguished on the TDS- $\delta^{18}O$ plot (Fig 6). These processes (namely, evaporation, dissolution and mixing) are the major mechanisms which are responsible for the observed range of the dissolved solute contents and the stable isotopic composition of the studied samples (Table 1).

Where local recharge of coastal aquifers is an active process, rainwater infiltrates first through the topmost soil. In the case of the studied area, this surface layer could be on sand dunes or in depressions between dunes. Depending on sediment thickness, soil solution progressively percolates downward after consecutive showers until it reaches the water-table over the years. Under relatively high recharge rates that favor aquifer replenishment in the temperate zones, it is generally believed that the seasonal fluctuation of the isotope signature of individual precipitation events is (more or less) “smoothed-off” when reaching the local groundwater reservoir, i.e. the observed groundwater isotope composition ($\delta^{18}O$ and $\delta^{2}H$) is very close to the “weighted” mean of local precipitation. Under rapid replenishment conditions, annual sinusoidal isotope function (i.e. the relationship of the rainwater isotopic content and time) can also be observed in groundwater, but with a rather reduced amplitude.

Moisture, chloride and isotope (deuterium) profiles

A rough estimate of residence time (t) could be obtained for the temperate zone areas using the following approximation (Philippe Olive, 1995):

$$t = \frac{A / B}{2\pi} \qquad \text{with:}$$

A amplitude of rainwater isotope composition change.

B isotope composition of groundwater.
(where no seasonal sinusoidal isotope composition is observed in groundwater, the value of “a” could be replaced by the standard deviation of the isotopic composition in groundwater systems with long residence time).

However, when groundwater replenishment rate is low (as it is the case in the semi-arid to arid zones), the temporal fluctuation of the groundwater isotope signature cannot any more be observed. Nonetheless, the isotopic composition of groundwater related to the present-day water

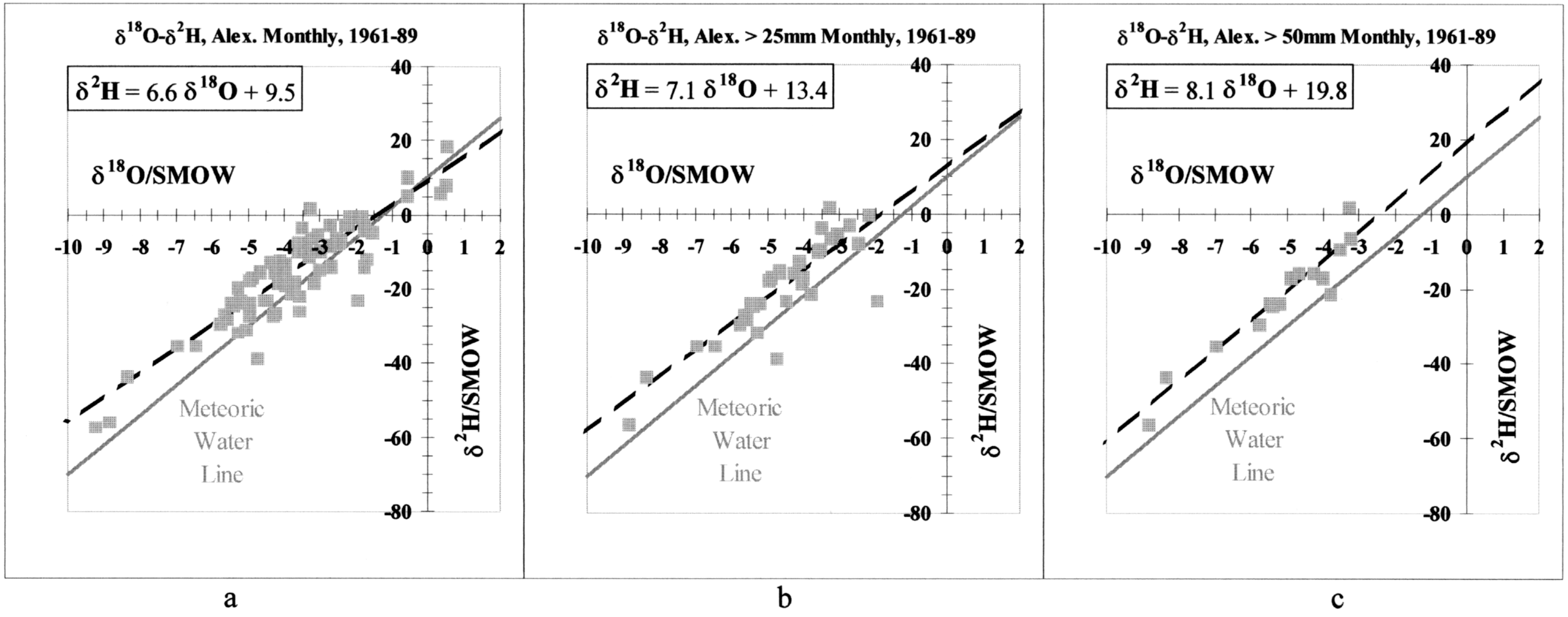
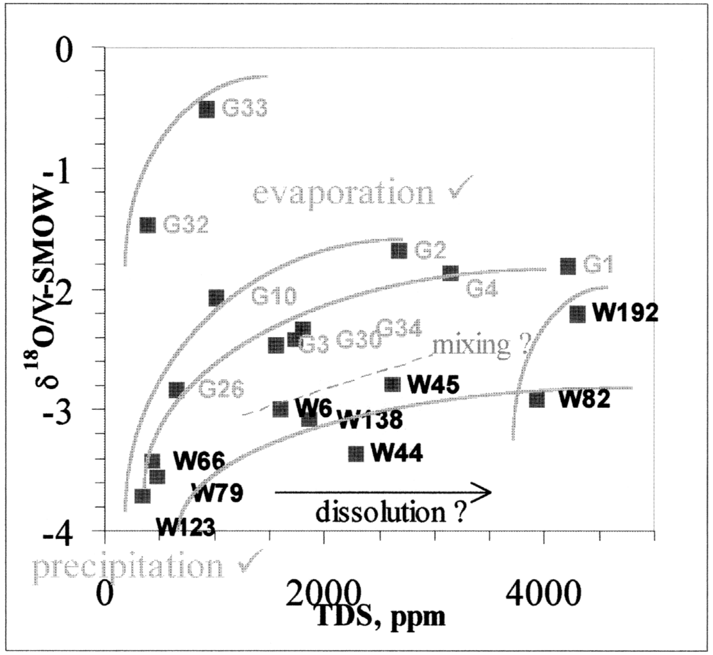


Figure 5. (a, b, c,) Isotope composition of Alexandria rains. The effect of low humidity in the eastern Mediterranean atmosphere is evident when the light rains are deleted. Scatter along the straight line fitted above the Craig line is due to different air temperatures.



Sample W=well G=gallery	TDS ppm	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰	d-excess ‰	interpretation
W 123	341	-3.71	-16.8	12.9	Medi. precip .dilute
G32	344	-1.47	-9.6	2.2	moderate.evapo.dilute
W 66	428	-3.42	-14.4	13.0	Medi. precip. dilute
W 79	471	-3.55	-16.7	11.7	Medi. precip. dilute
G 26	646	-2.83	-13.4	9.2	moderate.evapo.dilute
G33	849	-0.50	-3.4	0.6	moderate.evapo.dilute
G 10	1011	-2.06	-7.8	8.7	moderate. evapo.
G 3	1549	-2.46	-11.8	7.9	moderate. evapo.
W 6	1587	-2.99	-14.7	9.2	mixing ?
G 30	1713	-2.42	-11.9	7.5	moderate. evapo.
G 34	1793	-2.33	-13.3	5.3	moderate. evapo.
W 138	1858	-3.07	-17.3	7.3	mixing ?
W 44	2362	-3.35	-14.0	12.8	Medi. precip. dilute
W 45	2613	-2.79	-12.3	10.0	mixing ?
G2	2822	-1.67	-13.7	-0.3	more evapo.
G4	2848	-1.86	-10.3	4.6	more evapo.
G 22	2953	3.64	20.5	-8.6	highly evapo.
W 82	3795	-2.91	-18.6	4.7	more evaporated
G1	4243	-1.80	-12.4	2.0	more evapo.
W 192	4287	-2.19	-22.1	-4.6	more evaporated
Sabkha	108113	5.46	17.4	-26.3	highly evapo.

Figure 6. and Table 1. Isotope composition & TDS of groundwater and gully samples.

cycle (i.e. the non-fossil groundwater) in Sinai desert could be wide spread (and probably changes with time in the systems) due to the various water sources, multiplicity of the involved mechanisms and due also to the fact that (with the prevailing aridity) a small shift in recharge mechanism lead to large change in the water balance (Gat and Issar, 1974). For the area we have no long record for precipitation isotope composition. The nearest observation station where a rainwater isotope record was reported is that of Alexandria (IAEA, GNIP reports for the period 1961-1989) at some 400 km to the east of the studied sector. Unfortunately, we do not posses any time-series for Tritium nor for stable isotopes for the studied area. Due to these difficulties, the archive of the chemical and isotope composition of moisture preserved in the unsaturated zone could be referred to in order to estimate the recharge rate rather than depending on the groundwater isotope composition.

The fist outstanding observation in the studied moisture profiles is that of the borehole close to the shoreline (Abo-Tabl site) at 1 km from the present-day beach. The archive of sediments down to 20 m below land surface in this borehole has much lower moisture content in most layers (Fig. 14 and 15) compared to the borehole of inland site (Karafine site) laying at 10 km far from the shoreline. This outstanding moisture profile difference could not only be justified by the slight contrast in texture (Figs. 7 and 8); in fact the two boreholes have more or less comparable and vertical homogeneity with respect to texture (except in the bottom of the second borehole). For five sub-samples taken from different depths in each profile (0.0-0.5, 4.5-5.0, 9.5-10.0, 14.5-15.0 and 19.5-20.0 m), particle size distribution analysis indicates that Abo-Tabl samples belong to the sandy texture whereas Karafin samples are belonging to texture classes ranging from sand to silt loam. However, the clay content hardly exceeds 10 % in Karafin (except at the bottom layer where it is slightly more than 11%). Also, dry sieving (Fig. 7) showed that the materials of Karafin profile have three dominant grain sizes (0.50-0.25, 0.25-0.10 and 0.10-0.05 mm, and the mean contribution of the 0.25-0.10 mm fraction is higher than 60% of the total sediment material, whereas the mean contribution of the 0.50-0.25 mm fraction is 14% and the contribution of the 0.10-0.05 mm fraction is 21%). Hence there is a more gradual change in the cumulative particle size diagram of Karafin profile with the mean values showing that 85% of the Karafin sediments is <0.25 mm in diameter whereas 25% of the Abo-Tabl material is <0.25 mm. Since, the observed slight contrast in texture could not be the unique reason of the observed change in moisture profile, there should be an additional reason behind the differences in recharge history. This could be the presence of certain precipitation rate gradient inland (increase of rainfall at moderated distances from the shoreline compared to rainfall at the immediate shoreline). However, it is clear on the moisture characteristic curves (Fig. 10) that the finer sediments of Karafin retain higher moisture at the matric potentials 0.50 and 1.00 bar (509 and 1019 cm H_2O, or 50 and 100 kPa, that correspond to pore sizes of 6 and 3 **μm**, respectively) than the sediments of Abo-Tabl:

- volumetric moisture contents at 50 kPa: from 0.0552 to 0.0900 (mean 0.0720, i.e. about ***7%)*** for Abo-Tabl *versus* from 0.1433 to 0.1663 (mean 0.1583, i.e. about ***16%)*** for Karafin,
- volumetric moisture contents at 100 kPa: from 0.0441 to 0.0730 (mean 0.0591, i.e. about ***6%)*** for Abo-Tabl *versus* from 0.0805 to 0.1194 (mean 0.0889, i.e. about ***9%***) for Karafin.

Moreover, the meaning of the low moisture content at Abo-Tabl site could also be that recharge water passes through the unsaturated zone to the water-table *faster* than in Karafin site which retains higher moisture content “trapped” in the unsaturated zone (fortunately for our study!). Another impact is that evaporation from Abo-Table site is easier than from Karafin site; this is observed as higher Cl concentrations in Abo-Table site at 7 m below land surface than Karafin site.

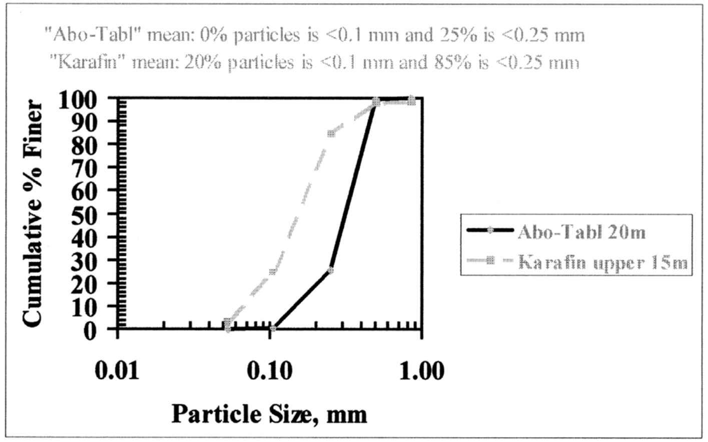


Fig. 7.

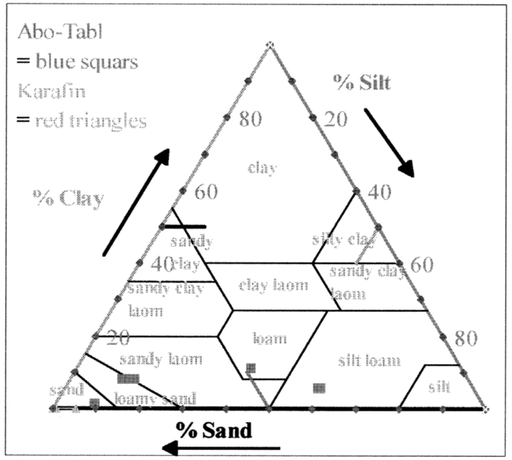


Fig. 8.

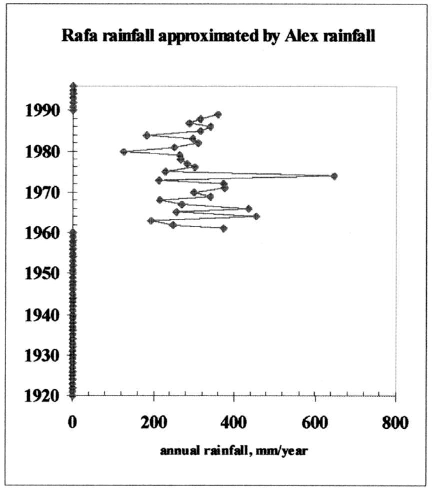


Fig. 9.

Figure 7. Dry sieving results.
Figure 8. Texture class of the upper layers (Abo-Tabl = sandy, Karafin = loamy sand, sandy loam, loam and silt loam).
Figure 9. Major rainfall event, 1975.

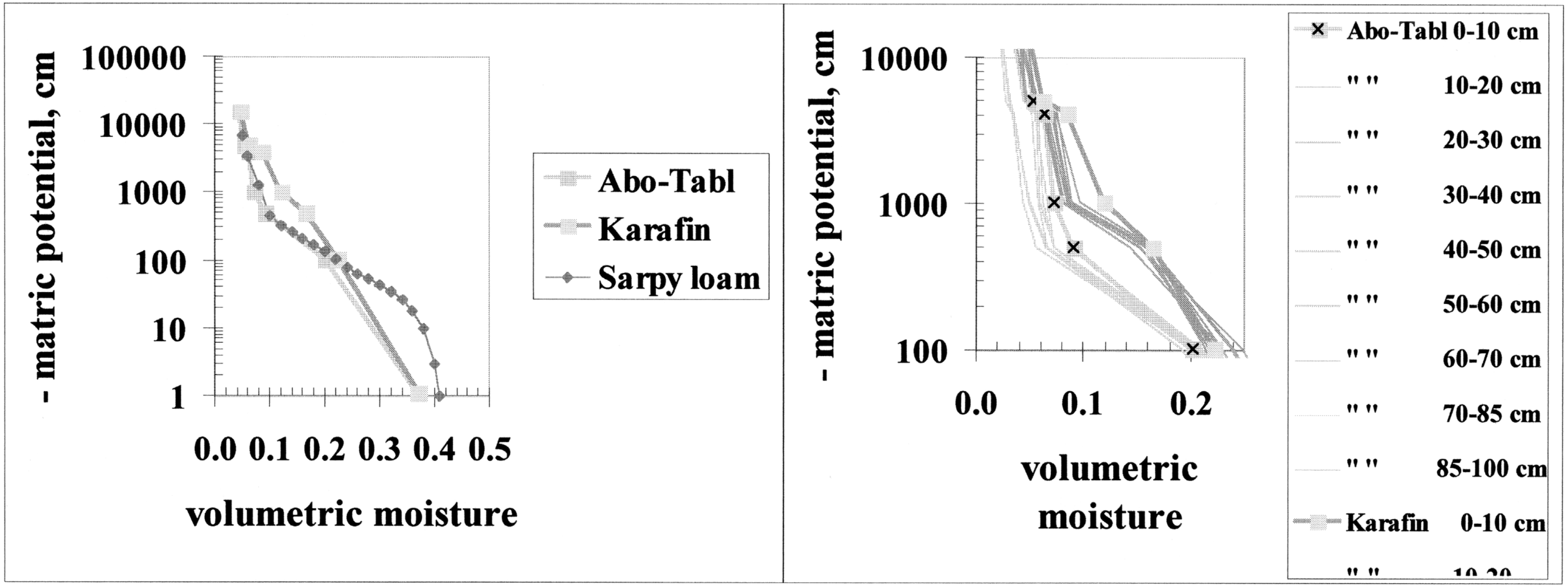


Figure 10. Mean moisture characteristic curves "pF" for 10 cm laminations (and means of the upper one meter thick of two bore-holes compared with the reference loamy soil "Sarpy").

Only at the surface layers (0-2 m deep) the two boreholes have comparable very low volumetric moisture (θv) contents which are generally less than 4%. Starting at a 2 m below land surface, θv gradually increases in both profiles to less than 7% at a depth of 6 m, with a relatively rapid increase in the inland profile (Karafin) than the shoreline profile (Abo-Tabl). In Karafin site, at the interval 6.5-7.0 m θv is less than 5%, but it suddenly increases to about 13 % at the depth interval 7.5-8.0 m, then increases again to about 20% at the interval 9.0-9.5 m. This is the first important peak in Karafin. A comparable peak is also found at the interval 14.5-15 m, and a third significant peak (θv = 21 %) also exists at the bottom layer 19.5-20.0 m deep. No such comparable notable peaks exist in Abo-Tabl profile. In Abo-Tabl, there is only minor changes in moisture with depth, and all moisture contents are in the narrow range 3.5-7.0%.

Coupled with the chloride vertical distributions, we can see that the upper six meters of sediments in both bore-holes show a net evaporative trend (decrease of moisture content and increase of Cl concentration toward soil surface), with a higher Cl concentrations in sediment moisture in Karafin site, probably due to the higher moisture reserve that plays the role of a reservoir that slowly evaporates, whereas in Abo-Table moisture flow could be more rapid downward. The outstanding feature here is that Cl peaks are more obvious at shorter intervals (and are arranged as the indentations of a wood saw) in Abo-Tabl than in Karafin and both are inversely related to moisture contents.

This trend could be interpreted by the mode of water loss and chloride content increase. In fact in a coarse-grained sediment with a low moisture content (here Abo-Tabl), all the arriving moisture content is easily made “available for evaporation”, whereas in a more fine material higher moisture content is retained against gravity and only water in large pores could be evaporated (and its Cl content increases). The fine and meso interstitial pore spaces will not be directly exposed to soil air. Also, the relative humidity in air in the fine pores could be close to saturation, hence evaporation of moisture retained in the fine pores would be minimized. The overall effect will be a “retardation effect” that “smears-out” the development of acute changes in Cl concentration in the fine-textured unsaturated zone (Karafin borehole). Moreover, this “delay” is further subjected to another “smearing-out” upon the arrival of the novel moisture by recharge during the following wet year. The net effect will be such that Cl peak in the finer materials will be “less spiked” and “wider” than in the coarser profile (Abo-Tabl) and could exist in higher positions (than moisture peaks) in the fine-grained profile.

We already know that the year 1975 has known an exceptional rainfall in Northern Sinai (Northern Sinai Governorate historical meteorology data, personal communication). We also know that the year 1974 was an exceptional year of high rainfall in Alexandria (IAEA GNIP, Internet consultation, 1999). Accordingly, we can look after these two major input pulses in Karafin profile at a position slightly deeper than 6 m below land surface (a position that corresponds to the year 1975 on the right-hand axis of the double-y-axis diagram, Fig. 15). This particular depth has already been defined by the vertical distributions of chloride and moisture and the corresponding calendar years in Karafin profile through the spreadsheet model (CHLEAR) prepared by the author. Then, from the difference in position (in meters) and considering that time needed to allow such downward shift of the 1975 moisture peak, Fig. 9, (the period in years between the year 1975 and the year of observation, 1998), we can obtain an estimate of the effective downward moisture flow velocity.

Effectively, at 9 m deep we find a major moisture peak which we shall consider as the remnant of the 1975 heavy rainfall pulse. If we a made a comparison between this observed depth (9 m), with the depth of 6 m calculated for that same important signal, we can estimate the effective mean velocity of moisture downward movement as:

(09.00 - 6.00) / (1996 - 1975) = 3.00 / 21 = 0.143 m/year = *14.3 cm/year.*

For the second known major rainfall of 1947 (for which the corresponding calculated depth is 13 m using the CHLEAR model), the signal is now at a depth of 19.75 m, this means that the effective mean velocity is:

(19.75- 13.00) / (1996 - 1947) = 6.75 / 49 = 0.138 m/year = *15.8 cm/year,*

which is in good agreement with the above given velocity value. In order to know the year of the signal found at depth 14 m, we can inversely use this information to know that the position of moisture of such event is in the middle of the time interval between 1975 and 1947 i.e. in:

1947 + [(1975 - 1947) / 2] = 1947 + [28 / 2] = 1947+14 = 1961.

which corresponds to the depth of 9.5 m, and by direct calculation we get (for verification purposes) a velocity of:

(14.25 - 9.50) / (1996 -1961) = 4.75 / 35 = 0.136 m/year = *13.6 cm/year.*

Once again this value is in a good agreement with the previously obtained one for the previously mentioned two high rainfall events of 1975 and 1947 (14.3 and 15.8 cm/year). However, through the historical meteorological data, the year 1961 must be first verified as a year that has really knew a high rainfall in the studied area.

year of Observation * years	**peak depth, m**	**year of event**	**calculated peak depth, m**	**distance traveled, m**	**time, years**	**velocity m/year**
1996	9.00	1975	06.00	3.00	21	0.143
1996	9.50	1961	14.25	4.75	35	0.136
1996	13.00	1947	19.75	6.75	49	0.158

***observation year is 1998, but the calendar year assigned to the upper layer in the studied profiles is 1996.**

Form these three estimates, the mean vertical velocity is 0.146 m/year (i.e. 0.039 cm/day). Compared to the velocity of saturated moisture in sands (which is in the order of 5-10 cm /day), the obtained values correspond to a real unsaturated flow phenomena not to any pretended flow under saturation conditions. However, this approximate estimates of water moisture transmission velocity are refined as reported in the CHLEAR model prepared by the author for this work.

Physical data and hydrodynamics

Despite the fact that Abo-Tabl profile has a coarser texture than Karafin profile in general (something which makes us expect higher bulk density for Abo-Tabl than for Karafin), the calculated bulk densities of Karafin are significantly higher. This interesting observation can be justified by the theoretical arrangement of the finer particles (in Karafin) within the interstitial spaces between larger particles. On the plot of Cl versus θv of Karafin borehole (not shown) two populations of data points are recognized. The first corresponds to the lower layers (below 7 m with relatively low Cl concentrations and high moisture contents) and the other corresponds to the upper layers (above 7 m with higher Cl concentrations and low moisture contents). The same observation applies to Abo-Tabl site but with much restricted ranges for the high Cl and low moisture for all layers in a manner that makes the whole Abo-Tabl borehole seems as if it were a a part of the upper layers of Karafin borehole. However, despite the lack of enough moisture reservoir in the lower layer at Abo-Tabl, the general relationship Cl-θv of both fits to a curvilinear increase of Cl with moisture decrease reflecting that the effect of evaporation is not the unique mechanism other wise Cl would increase linearly with θv decrease. This means that the evaporative losses are significantly compensated by recharge input water that mixes with the residual water. In fact at the observed Cl concentration Cl is conservative, consequently Cl concentration will linearly increase with evaporation from an initial water pool with C_0 mg.l^{-1} Cl to C_1, C_2, … etc. mg.l^{-1} Cl before and after successive stages of evaporation, respectively (where the slope of the linear fitness corresponds to a concentration factor), and any deviation below this straight line must reflect water input. In fact the observed non-linearity of the Cl-θv relationship can be segmented into a lower branch that reflect mixing with input water and low evaporative flux (form the lower borehole layers) and an upper branch that reflects that evaporation flux is higher than the recharge rate. This trend has be modeled in the spreadsheet CHLEAR for this work and nicely fit tot the observations.

On the δ^2H-θv plot (Fig. 13), a trend similar to the Cl-θv plot is also obtained. However, δ^2H values of many lower layers are similar or even higher than δ^2H values of the upper layers in the two boreholes. This is very interesting observation since it would indicate the role of the lower borehole layers as a reservoir of evaporative flux (hence its high stable isotope contents) and the continual arrival of isotopically-depleted recharge water through the upper layers. This observation also reflects the different behavior of pollutants (hear Cl) and the integral water molecule composition (here the stable isotope ratio ^{2}H/^{1}H) under the intricate effect of evaporation, recharge and mixing. Chloride concentration increases in the upper layers by evaporation both from input water arriving through infiltration and from moisture reservoir in the lower layers. The same role applies to Deuterium in the upper layers, however, the stable isotopes are subject to two types of fractionation during evaporation: the equilibrium and the kinetic fractionation that could partially be compensated by mixing with new input water with different (depleted) isotopic composition and these depletion could probably make the isotopic composition of the mixture more depleted than the isotopic signature of the older moisture reserve before replenishment in any given year. Also, moisture in the lower layers could have a longer residence time than moisture in the upper layers, so their isotopic composition gradually become more enriched than the upper layers with time. Condensation could also take place in the base of the upper layers due to temperature gradients giving rise to a local isotopic depletion in the base of the upper layers. A final explanation is that the whole isotope archive of moisture in the unsaturated zone is subject to the relatively wide range of the isotope compositions of rainwater in the last decades due to differences in air temperature during raining-out. In a sense, the isotopic composition of the upper layers is the residual composition of rainwater fell during more recent years than in the case of the lower layers and these more recent years could have been already more isotopically depleted than before. Abot-Tabl profile is characterized by a more clustered isotopic and chloride content pattern on the δ^2H-θv plot than Karafin borehole indicating, once more, higher evaporative losses (hence lower recharge rate if rainfall rate was similar on the two sites) than Karafin profile. The δ^2H-Cl plot (not shown) once more confirm the previously given explanation and supports the idea that recharge rates of the recent years was probably lower than in previous decades archived in the lower layers and the role of the lower layers as a retardation reservoir (in particular the relatively fine-grained lower layers in Karafin site) that is filled and keeps moisture from downward flow to the water-table (hence moisture has longer residence times). In fact, moisture flow velocity (calculated by the model CHLEAR) in Karafin site is on the average about 0.60 that of Abo-Table site (mean = 0.46 m.y^{-1}) and increases downward from about 0.30 to about 0.20 my^{-1}. However, de to fact that the mean volumetric moisture content in Karafin profile is 0.12 whereas that of Abo-Tabl is 0.044, the mean moisture flux in Karafin is about 31 mm.y^{-1} whereas that of Abo-Tabl is only about 20 mm.y^{-1}

(Fig. 18). These hydrodynamic parameters reflect that Karafin profile transmits water more effectively to the water-table. Moisture content in pores in Karafin is much higher than that at Abo-Tabl. This means that the relative humidity in the air-spaces of the interstitial pores in Karafin is high. This could stand against evaporation in particular form the unsaturated lower layers. Despite the coarse texture of the studied boreholes, the ulk density at Karafin site is significantly lower than in Abo-Tabl, i.e porosity is low in Karafin compared to Abo-Tabl. This could be the resultant of the natural packing of the fine-grained particles (found in particular in Karafin) inside the larger pore space between the larger particles. This observation explains the retention of higher moisture content in Karafin sediments at the matric potentials 50 and 100 kPa compared to Abo-Tabl sediments. These two matric potentials correspond to 6 and 3 μm pore diameter, respectively. This means that the higher fraction of Karafin moisture is trapped in fines pore spaces than in Karafin, and this, once more, stands against water loss by evaporation (which is confirmed by δ^2H contents which are more depleted n Karafin than in Abo-Tabl). In a field experimental study of the saturated hydraulic conductivity of the surface layers, it is found that K_{sat} in Abo-Tabl (mean = 34 m/day) is about 20 times that of Karafin (1.6 m/day). The unsaturated hydraulic conductivity will reported elsewhere.

The recharge rate at the two sites was estimated through the model CHLEAR prepared for his work. For Karafin it was found to be about 37 mm/day whereas in Abo-Tabl it is only 18 mm/year. Calculating the calendar years and the residence times, it was estimated that due to moisture velocity differences, the historical record of Abo-Table moisture is about 40 years, whereas that of Karafin is about 80 years, i.e moisture found at the bottom of this 20 meter-thick unsaturated zone corresponds to the rainfall of 1920 (Figs. 11 to 15). Consequently, there is a great chance to fined the 1963-thermonuclear Tritium peak at moderate depths in the unsaturated zone of this site and at lower layers in Abo-Tabl, however, Karafin site is preferable for such study due to its higher moisture contents in the lower layers.

Position of the 1963-tritium peak in the Vadose Zone

When the water-table is several meters (to several tens of meters) deep, and the percolation moisture is slowly moving downward to an unconfined aquifer that is exclusively receiving recharge through the upper unsaturated zone (i.e. without replenishment from other sources such as lateral seepage from adjacent formations), it is highly probable that the famous thermonuclear Tritium peak of the year 1963 would still be found somewhere above the water-table in the unsaturated zone. If that Tritium peak is analytically observed only in the unsaturated zone (not in the underground water), an independent estimate of the recharge rate could also be calculated and compared to the recharge rate obtained from the chloride mass-balance in the unsaturated profile and the CMPA model turns into a chemical-Isotope-Moisture profile archive (CIMPA) model (sea the CHLEAR spread sheet model for the predicted depth of the 1963-Tritium peak).

If, however, Tritium is analytically found in groundwater, whereas the 1963-Tritium peak is also found in the unsaturated zone or its position is predicted (using an estimate of the time laps required for moisture transmission as calculated on a calendar basis from Cl profiles as done by the spreadsheet CHLEAR model), Tritium content in groundwater should be understood (only in this case) as arriving to the local aquifer not only by downward flow of moisture across the unsaturated zone but also through lateral flow from an adjacent underground system. In this last case, the used approach will still be helpful as it elucidates the hydrological system and makes the regional groundwater replenishment issue much better understood. This particular piece of information could be highly important for modeling aquifer parameters using time-series Tritium contents in groundwater. Moreover, the stable isotope (Oygen-18 and Deuterium) could enhance our understanding of the intricate succession of recharge and evaporation during long-term recharge through the unsaturated zone.

Further modeling

Modeling Tritium in groundwater is normally based on the lumped parameter methods (Maloszewski and Zuber, 1982, Zuber, 1986) known as the black box models. In these methods, the reconstruction of the Tritium output time-function (Tritium content change in groundwater with time) is theoretically obtained using a known Tritium time-series input data set (tritium content change in local water source through time) and a quantitative theoretical approach (model that can be run on a computer) that respects and corresponds to the hydrological settings of the aquifer. Thereafter, a minimization fitness procedure or the try-and-error method (Fahmy Hussein M., 1994) is used to best fit the observed tritium time-series output (actually measured in groundwater samples taken from local wells or springs) to the theoretically-predicted tritium output time-series (model output) in order to obtain the aquifer parameters (mainly the turn-over time and the recharge rate).

Obviously, the exercise of Tritium modeling in groundwater needs the availability of tritium time-series input function in local rainwater (including the early 1960’s peak) and collecting observations (for several year) on tritium contents in pumped groundwater. Unfortunately Tritium input functions are not available in many semi-arid to arid areas in the world due to the poor distribution of observation stations in these climatic zones. When local monitoring is lacking, reference could be made to some other nearby IAEA station for Global Network of Isotopes in Precipitation (GNIP), but such station could be several hundreds of kilometers far from the studied area.

Evidently, the lack of Tritium input data is a tedious obstacle (in particular in Egypt where we have only two rainwater isotope monitoring stations (at Alexandria and Ras-Barrany0, and even these stations were functioning only for about 29 years (1961-1989). Moreover, the setup of an output monitoring needs a special agreement with an interested laboratory and the availability of good financial support from an external fund agency or the local national authorities, something which is not always possible. The first decade of the 21st century will be, for sure, the last chance for making such monitoring. After that timing, the continual decay of the atmospheric Tritium reservoir (which started after 1963 after the halt of the aerial thermonuclear bomb tests) will decline to return back to the normal Tritium content base-line in precipitation. Consequently Tritium, as an ideal natural tracer in isotope hydrology, will lose its present-day magnificent value.

Water movement in porous media is a complex natural phenomenon, however, theoretical platform exists for dealing with it on the basis of Darcy law and the continuity equation. The combined equation gives a partial second-order differential type that can hardly be solved to obtain an analytical solution (only under rigid boundary conditions - and using restricted initial conditions if we deal with transient water flow -) to the extent that the obtained analytical solution is actually non-useful for application on other cases. Solute transport in the unsaturated zone is even a more complicated issue and needs (beside a coherent theoretical basis) solving the water flow regime first to get the values of the unsaturated water flow velocity. However, Fick’s law and source (and sinks corresponding to different solute inputs and outputs) presents a good framework for the problem. However, the second order partial differential form of this equation has no analytical solution. Nonetheless, soil physicists have had to overcome the dilemma by approximate solutions based on the initiation of a grid that represents data of the hydrological system at the specified nodes and a suitable numerical method in order to reduce the partial differential equations to matrices that can be upgraded within space (and time for transient problems) and solved on a computer using an appropriate algorithm to get good predictions on water and solute content in the regime within the used space and time.

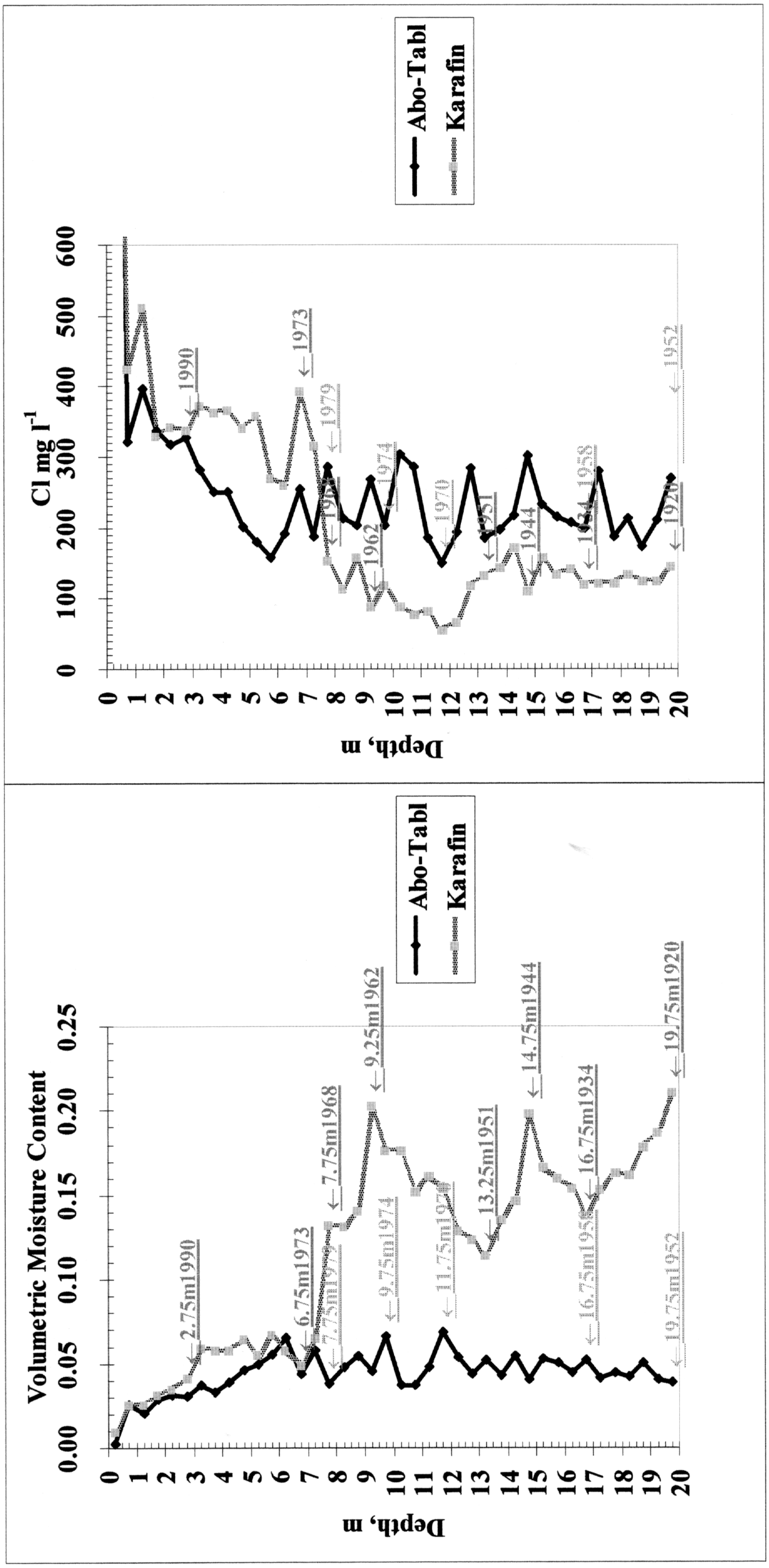


Figure 11. Moisture and chemical archive profiles and assigned calendar years.

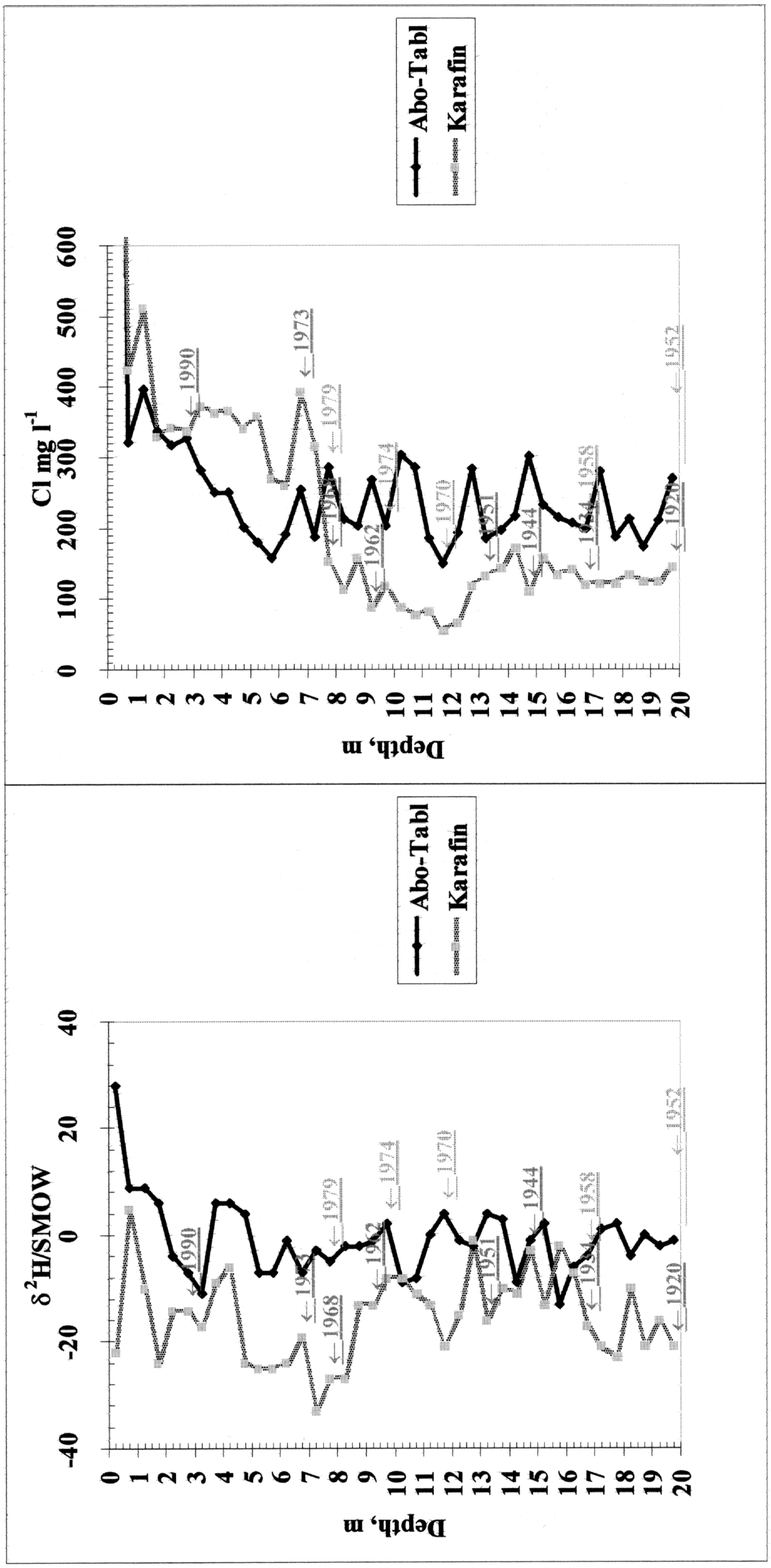


Figure 12. isotope and chemical archive profiles and assigned calendar years.

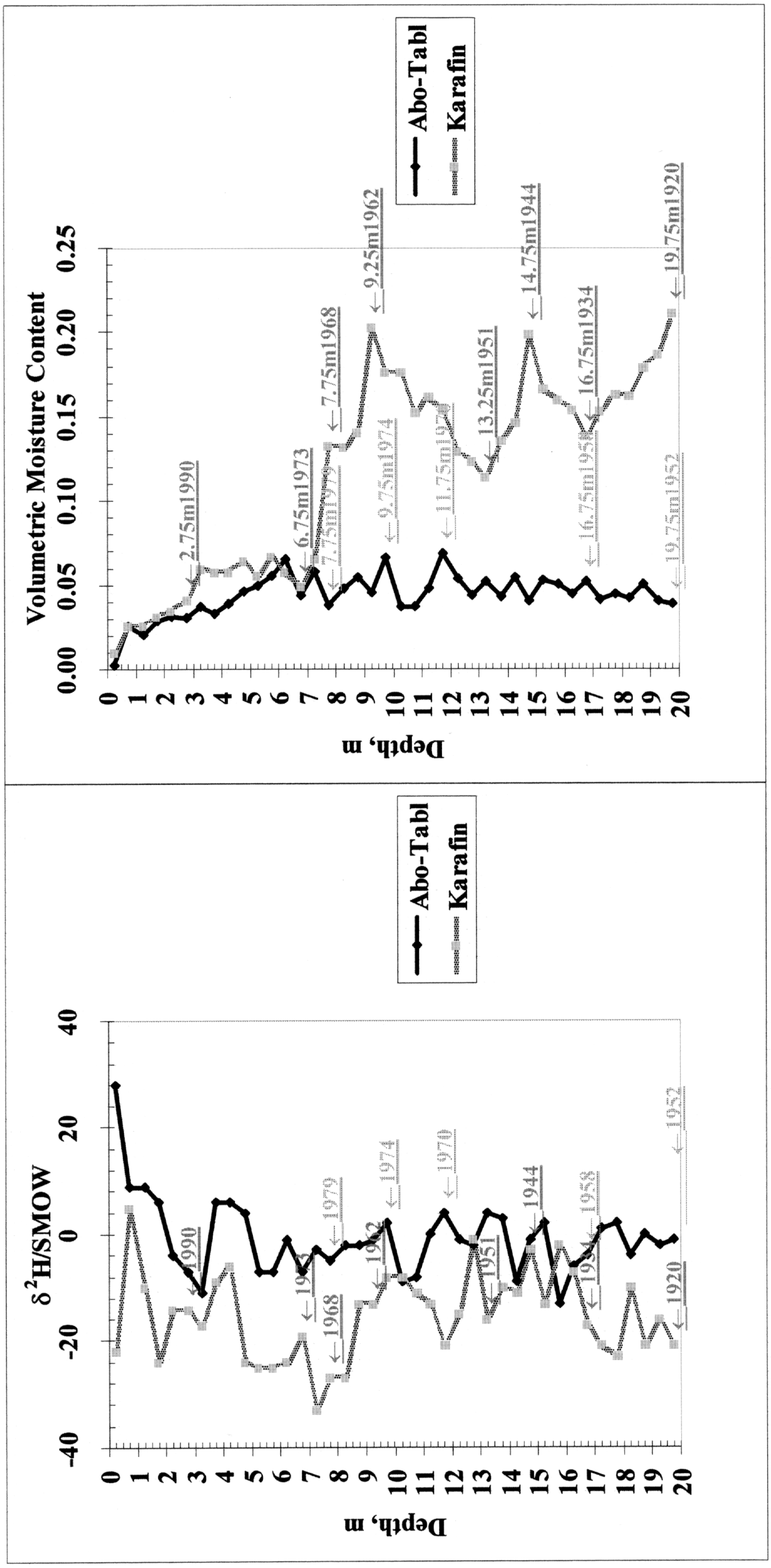


Figure 13. Isotope and moisture archive profiles and assigned calendar years.

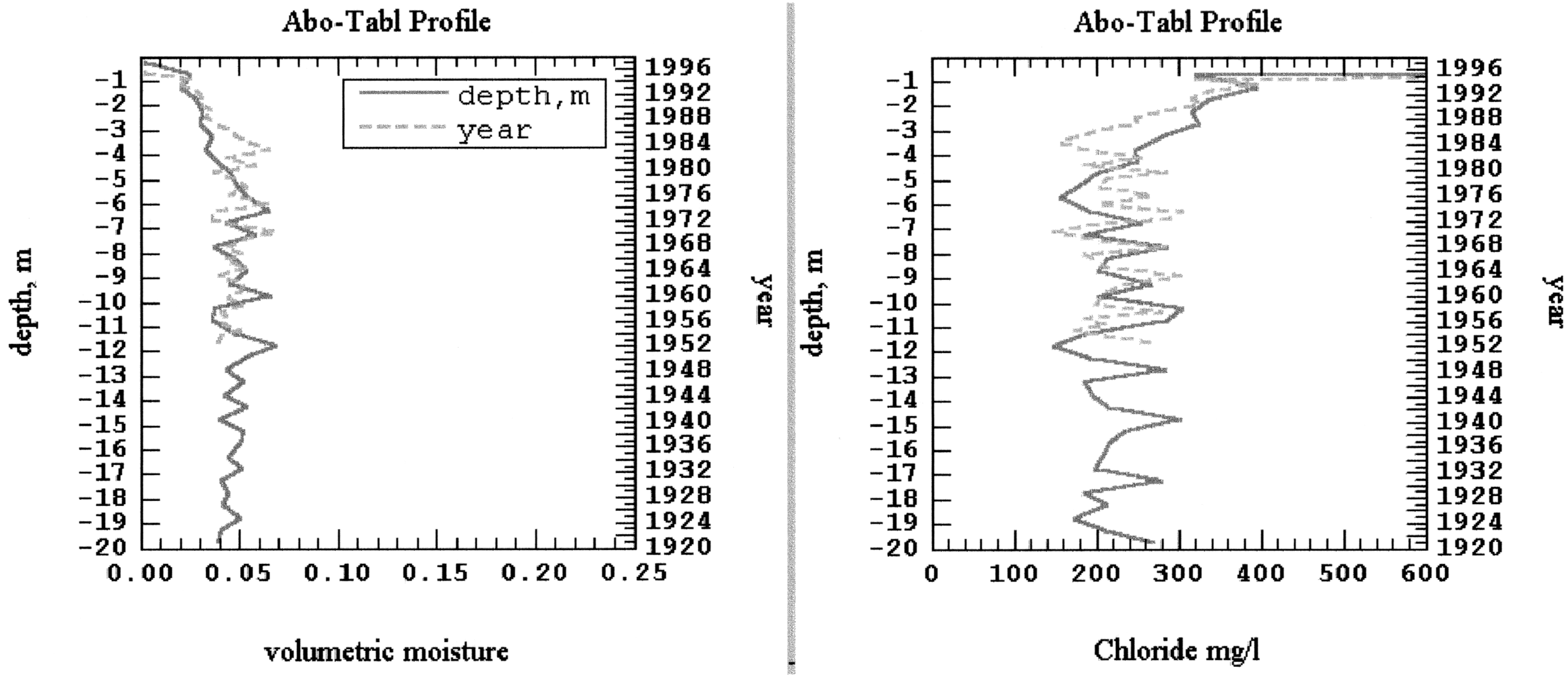


Figure 14. Moisture and chemical “Abo-Tabl” archive and assigned calendar years.

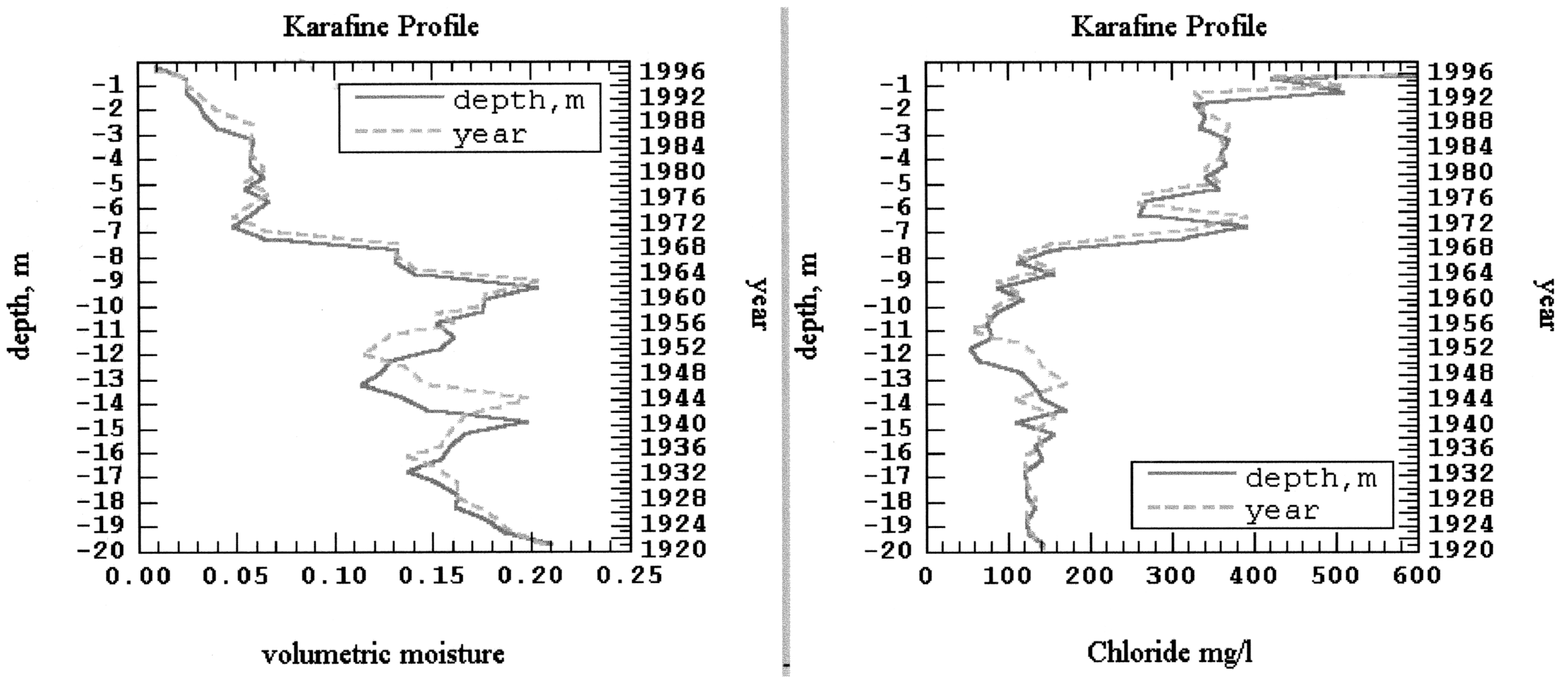


Figure 15. Moisture and chemical “Karafin” archive and assigned calendar years.

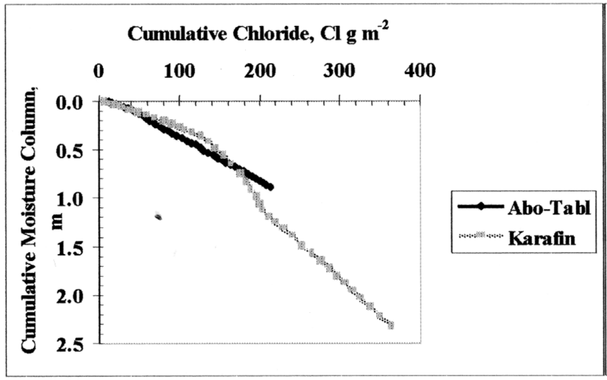


Fig. 16.

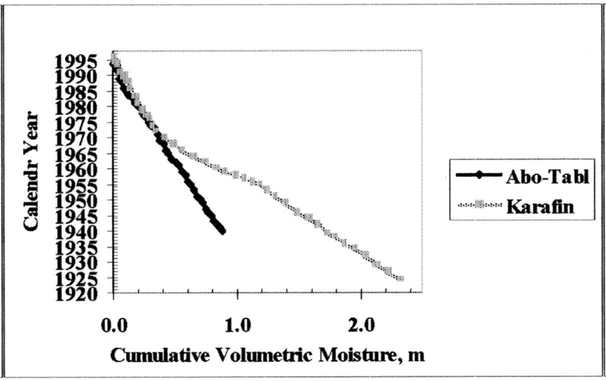


Fig. 17.

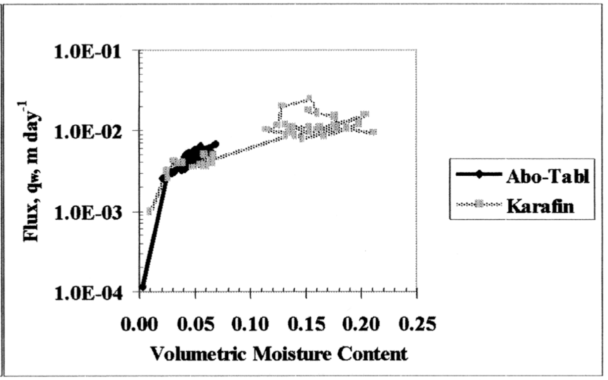


Fig. 18.

Figure 16. Cumulative Cl versus cumulative moisture.
Figure 17. Cumulative moisture versus calendar years.
Figure 18. Flux versus volumetric moisture content.

Figure 19. Landscape, dry-drilling of the boreholes, sampling and measurements in the Northeastern Coastal Plain of Sinai.

Normally such numerical solutions needs heavy calculations on computers and are very extensive for memory requirement and the real time needed to run the simulation. These machine and time requirements become overwhelming as the simulated problem is a complicated one. For the cases studied in soil physics, the usual use of such models is related to water and agrochemical applications during relatively short periods of time (several hours or days) and there is no need to run the simulation to represent the events and changes that could take place during several years or several decades. In our case, the flow of water to the water-table for recharging the aquifer is, on the contrary, a problem that takes place during much longer periods than the usual time limits used in soil physics and time increases with the increase of the unsaturated zone depth above the water table.

Moreover, before being able to run any soil physics model, the user must have a set of parameters measured in the lab and/or the field in order to know the relationship (function) between the moisture content and the potentials with which different moisture contents are hold in the unsaturated medium during the wetting (percolation and redistribution) and the drying (evaporation) cycles. Furthermore, another function (change of hydraulic conductivity with moisture content - or with potential -) is also needed in order to take the change of flow velocity (with moisture content change) into consideration. Clearly, these complications make such research difficult to a great extent. Some well equipped research stations use automated lysimeters and data loggers to get continuous monitoring of the needed information, but this is not available to every research worker in particular in the developing countries.

Despite the fact the global mass balance of water flow and global chloride mass balance could represent a bypass through these difficulties (when the flow system is considered as being of a piston flow type), it is obvious that the application of the physical background of the problem (based on Darcy, continuity and Fick's laws), despite its inherent difficulty, must not be completely abandoned and neglected altogether. A simple simulation should be undertaken (for example using one-dimensional flow regime and obtaining the p F curve and the K(?) functions from a simplifying model - like RETC (by Van Genschten) and using a simple simulation package - like CHEMFLO (by Nofziger and Ragender) for one-dimensional water flow and solute transport - and making the simulation space restricted to the upper layers of the unsaturated zone during relatively short time - one year or so - in order to get an idea about the major aspects of the predicted solution given by the physical approach.

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